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Developing an assessment framework for smart and sustainable buildings

Master’s Thesis, submitted as a partial fulfillment of the requirements for the degree of Master of Science in Technology

Espoo 22.11.2019
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Abstract

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Abstract

The building and construction sector is currently under tremendous pressure to cut its carbon emissions in the following years. Responsible for a significant proportion of the total greenhouse gas emissions worldwide, buildings play a vital role in meeting the climate goals set out in the Paris Agreement, keeping the global temperature rise within the safe limits. The rise of technology and recent development in smart building movement have prompted engineering and consulting firm Ramboll Finland Ltd. to develop a new building concept called Smart and Sustainable Buildings (SSB), tasking this thesis work to help better define its definition and formulate an assessment framework to guide the development of smart buildings that achieve sustainability goals.

The thesis started firstly with reviewing the existing definitions and frameworks of green building and smart building to gain an understanding the key features of both concepts, resulting in a concise definition that can describe the new building concept for the clients and a list of indicators to form the basis of an assessment framework. Then a total of 23 indicators were selected for three main sustainability and smartness dimensions, representing a holistic approach. Lastly, an evaluation using the framework has been performed on a new and modern office building as a case study and it achieved an overall score of 3.4 out of maximum 5, corresponding to B-level which indicates a good performance by meeting the minimum standards according to the defined smart and sustainable classifications.

In conclusion, it is envisioned that the system will be beneficial to the building stakeholders' understanding of the building performance, to systematic data collection for monitoring purposes, and to benchmark against other equally comparable buildings.

Keywords Smart building, sustainable building, sustainability assessment, green construction, health and wellbeing, smart readiness indicator, energy flexibility

Foreword

This Master’s thesis has been carried out at Ramboll Finland Ltd. between April and November 2019. Initiated by Ramboll’s new building concept called Smart and Sustainable Buildings, this research aims to establish a common definition of a smart and sustainable building to facilitate the communication between the experts and the clients and to develop an assessment framework to measure building performance in terms of smartness and sustainability qualities. The thesis work is sponsored by Ramboll as an internal R&D project.

I am grateful to my employer Ramboll Finland Ltd. for allowing me to complete my Master's studies during my employment and for the opportunity to carry out this thesis. I would also like to thank the teaching staff and fellow students at Aalto University’s Advanced Energy Solutions program for the knowledge and support they have given to me over the short but memorable two years. With special mention to Mika Kovanen and Paula Rantanen for the thoughts and feedback they have shared, to Professor Markku Virtanen for his guidance and help during the thesis process, and to my colleagues at Ramboll for their assistance in developing the framework.

Last but not least, my deepest gratitude to my parents, brother Lộc and sister Trà for their unparalleled love and support, to Pinja and Upu for always being there for me. I am forever indebted to my parents for giving me the opportunities and experiences that have made me who I am today.

Espoo 22.11.2019

Vinh Phuc Huynh

Table of contents

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BASS	Building Assessment for Smartness and Sustainability
BPIE	Buildings Performance Institute Europe
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Methodology
CFC	Chlorofluorocarbons
CHP	Combined Heat and Power
CTBUH	Council on Tall Buildings and Urban Habitat
DELC CO_{2e}	Direct Effect Life Cycle CO_2 equivalent emissions
DG ENERGY	European Commission Directorate-General for Energy
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen e.V.
EBC	Energy in Buildings and Communities
EPBD	Energy Performance of Buildings Directive
EU	European Union
EuroACE	The European Alliance of Companies for Energy Efficiency in Buildings
GHG	Greenhouse Gas
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
ICT	Information and communications technology
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IWBI	International WELL Building Institute
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LOLP	Loss of Load Probability
MSDs	Musculoskeletal Disorders
nZEB	Near-Zero Energy Buildings
PMV	Predicted mean vote
PPD	Predicted percentage dissatisfied
PV	Photovoltaic
REC	Real estate and construction
SRI	Smart readiness indicator
SSB	Smart and Sustainable Buildings
UN	United Nations
USGBC	U.S. Green Building Council
WELL	WELL Building Standard
WGBC	World Green Building Council
WHO	World Health Organization

Table of Figures

Table of Tables

1 Introduction

1.1 Background

Over the last decades, there has been an increasing awareness of the impacts of the real estate and construction (REC) sector has on the environment. Buildings construction and operations were responsible for 36% of the world's final energy use and nearly 40% of the energy-related carbon dioxide emissions in 2017. (1) Dr. Fatih Birol (1) announced that the buildings sector is growing rapidly and will continue to do so over the next 40 years, with an expected 230 billion square meters of new floor area - an equivalent of the size of Paris every single week. Since the built environments account for a large portion of the global greenhouse gas emissions, it is obvious that this is the area where meaningful actions with the best efforts are needed. Nations were brought together at the COP21 in December 2015 in Paris where a historic agreement was made to keep the global temperature rise well below 2 degrees Celsius above pre-industrial levels and buildings will play a vital role to make this happen. According to the European Commission report '2050 low-carbon economy roadmap' (2), a cut of around 90% of the greenhouse gas emissions in the built environment by 2050 (compared to 1990 levels) is necessary to keep global temperature below 2ºC. For the European building sector, this means that all new buildings from 2021 onwards will have to be nearly or net-zero energy buildings. Many countries have already started implementing stricter energy performance standards for building, but efforts will need to be strengthened significantly. Recently, a special report published by the UN Intergovernmental Panel on Climate Change (IPCC) has warned that letting the global temperature rise above the 1.5ºC mark will consequently increase the risks of droughts, floods, extreme temperatures and poverty for hundreds of millions of people. (3) Urgent and unprecedented actions are needed across all sectors and industries to work together for global warming to be kept within 1.5ºC rise. Recognizing this problem, the World Green Building Council (WGBC) (4) has urged national and local policies to make all new buildings net-zero carbon by 2030 and existing buildings by 2050. The battle against climate change is well and truly on for the humankind's hope of a sustainable low carbon future.

The concept of sustainable development was first defined in 1987 by the United Nations (5, p.43) as "meeting the needs of the current generation without compromising the ability of future generations to meet their own needs.". Since then it has matured within the REC sector and the term 'green building' has been widely used and is associated with sustainability. Green building is a practical method of striving to make the best use of natural resources, considering the environment and achieving economic and social aspects. Green building is an important step towards sustainable development, however not all green buildings are indeed sustainable. The building industry has focused on the physical aspects of sustainability, i.e. reduced the environmental impact of buildings, without sufficient consideration for the human perspective and the end-users. Many buildings often fail to serve the present and future needs of the users and to deliver value to their owners and users over time. This leads to the inability of buildings to contribute to higher economic prosperity and identity in the community where they are located.

Truly sustainable buildings are attractive and healthy for the building users and at the same time have a low environmental impact throughout their life span as well as fulfill their social and cultural potential. At the same time, another concept so-called 'smart' or 'intelligent' building has emerged driven by the rapid growth of the Internet of Things (IoT)-related technology. In recent years, the way buildings operate and are used has drastically changed thanks to the complex interconnected structures, systems, and technology. The term ‘smart building’ is used to describe these kinds of buildings where the latest technologies are utilized to facilitate efforts towards energy efficiency, minimizing environmental impact over the life cycle while maintaining high building user satisfaction. Recent market report (6) indicates that the smart building market is expected to grow from 60.7 billion USD in 2019 to 105.8 billion USD by 2014.

However, there seems to be a lack of a shared definition of smart buildings which makes it difficult to identify a common trend within the field and create confusion among the parties involved. Smart building is a diverse concept with many perspectives and the vagueness of existing definitions can lead to misunderstanding and inhibits the development of the concept. Besides, the concept often says little about the substance behind the smartness and how it links to sustainability. While sustainability in the built environment generally addresses design concepts and principles and overlooks smart solutions, smart buildings tend to focus on ICT advancement and fall short of the sustainable design features. Subsequently, advanced technologies are being used without making many contributions to the urgent and pressing issues of sustainable development, and sustainable strategies are lacking new and better technologies that can help achieve sustainability goals. This mismatch between smartness targets and sustainability goals need to be addressed when striking for smarter, more sustainable buildings.

Located in the Zuidas business in Amsterdam, the Edge building is a prime example of a smart building that integrates most advanced technologies to create a healthy and productive working place for its occupants. With a total of 28,000 sensors that monitor every aspect of the indoor environment, the Edge is considered to be the smartest building and also the greenest building on Earth with the highest score ever given for BREEAM (Building Research Establishment Environmental Assessment Methodology), one of the most popular green building rating systems in the world. This demonstrates an ongoing transition of the building industry into the digital age, where technologies are used to create better buildings that are sustainable and enhance the lives of their occupants. (7)

Together with green building certification systems, building owners and developers now have a wide range of smart building technologies at their disposal to create more sustainable and intelligent buildings. This, however, creates new challenges. Whether it is ‘green building’, ‘sustainable building’ or ‘smart building’, it is clear that we are living in an information technology era and old-fashioned, unconnected and unsustainable buildings are no longer viable. The ultimate goals of buildings of today are to provide the best indoor environment and user experience, to consume the minimum of resources, to minimize greenhouse gas emissions and to have a positive impact on the economy and the society. The hypothesis is that buildings can be smart, sustainable and a good investment for the building owners. For this to happen, the stakeholders need to have a better understanding of the needs and expectations of the potential users, and the various components in the smart building, how they interact and what benefits they bring.

1.2 Objectives and research questions

The main objective of this thesis work is to create a smart and sustainable building assessment framework to guide the development of buildings that are not only considered to be smart but also to achieve their sustainability goals. As the initial step, an overall understanding of the current smart building development should be obtained by reviewing the literature on smart buildings. This work would lead to the formulation of a possible definition of the smart and sustainable building concept. To create the assessment framework, the relevant key performance indicators should be identified from green building standards and smart building researches. The focus will be placed on topical issues such as building user experience, carbon-neutrality, climate resilience, and energy efficiency.

The main research questions of this thesis work are:

1. What is the definition of a smart and sustainable building?
2. What are the key performance indicators of a smart and sustainable building?
3. Can the performance of such buildings be measured?

1.3 Research methodology

To answer the research questions mentioned in the previous section, this study comprises of two parts:

(1) Theoretic part: a literature review on sustainable buildings and smart buildings
(2) Empirical part:
- Qualitative: identifying the key performance indicators and developing a smartness and sustainability assessment tool
- Quantitative: performing an assessment of the system on a case study building

The overall research process can be seen in Figure 1. The research methodology is explained in more detail below.

Literature review on smart and sustainable buildings
To gain an overall understanding of the topic, a literature review is conducted. It can be said that sustainability in the built construction has been well defined by various institutions, organizations and standards all over the world, such as the green building standards. On the other hand, there is no one common definition of what a smart building should be, even though the terms ‘smart building’ or ‘intelligent building’ might not be new. Only until recent years has smart building become an emerging trend in the building and construction industry. This thesis looks at smart building studies and researches to find out what aspects that make a building to be considered as ‘smart’, what features they should have and what benefits they should bring.

Identifying the key performance indicators and developing a smart and sustainable building assessment tool
The findings from the literature reviews are used to identify the key performance indicators of the concept of a smart and sustainable building. A set of criteria is needed to select the most relevant and desirable indicators. The chosen indicators form the basis of the smart and sustainable building assessment index.

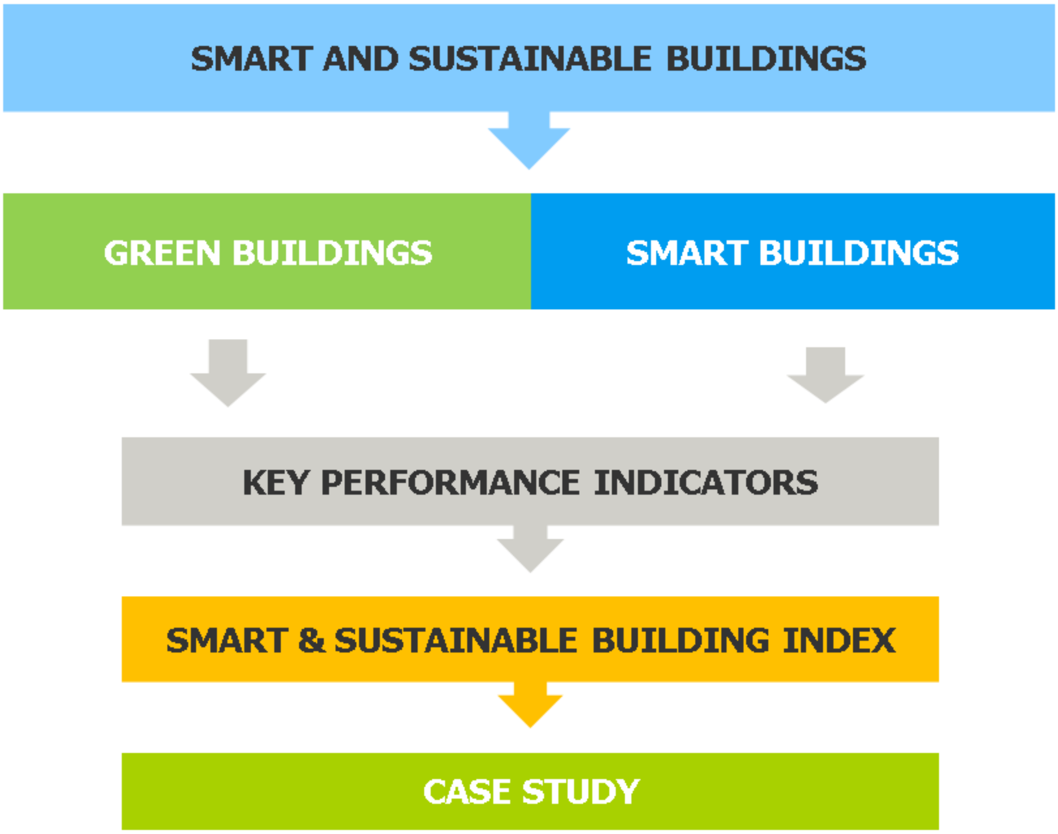

Figure 1. The overall thesis process.

Performing an assessment system on a case study building

As the index has been developed, an assessment is performed on a new office building as a case study. The case study building is a new office building located in Espoo, Finland. The assessment measures the building performance of various sustainability and smartness aspects, resulting in a final 'smart and sustainable' score.

1.4 Thesis structure

The body of the thesis is structured in four chapters. In chapter 2, the megatrends in today's green buildings, existing definitions of smart building and the key features drawn from those definitions, as well as the European Commission's initiative to raise awareness of smart building technologies through the establishment of the Smart Readiness Indicator (SRI) for buildings are discussed. Chapter 3 describes the structure of the Smart and Sustainable Building Index, including the key performance indicators (KPIs), their definitions, calculation, and benchmarking methodology. An assessment of the index is performed for a case study building, which is presented in chapter 4. The results of the case study assessment and discussions of the findings are in chapter 5.

2 Smart and sustainable buildings

2.1 Green building trends

World Green Building Council (8) defines sustainable or ’green’ building as a building that, throughout its entire life cycle, has minimal impacts on the environment and even contribute positively to the society and the planet. The environmental movement started in the 1970s due to the oil crisis but not until the early 90s, when the first Green Building Council was founded in the US, the global green building movement was formally born. (9) It began to generate a lot of interest in the building and construction sector around the world and today is one of the fastest-growing building design and construction concepts. In the latest report 2018 World Green Building Trends (10), almost half of the total respondents say that 60 percent of their projects would be green buildings by 2021. The report also states that green building activity would continue to grow across the globe with a very strong increase in many countries over the next three years, claiming the growth in green building is driven by environmental regulations and strong business benefits leading to higher demands from the clients. Also, creating healthier buildings for the occupants has become increasingly important for the green building market. Additionally, the Sustainable Buildings Market Study 2019 conducted by Ramboll (11) points out that the top five key future trends of green building activity are:

- Life cycle thinking and management
- Health and wellbeing
- Increased focus on carbon neutrality
- Resilience against climate change
- Digitalization

Green building is also quickly becoming the standard of the building and construction industry. The demand for healthier and more sustainable buildings is driving the real estate market toward the green movement. As green building becomes a common trend, green building rating systems and certifications also become a client’s expectation in building projects. There is now an extensive number of standards, ratings, certification programs available in the marketplace to drive the green building movement to create more sustainable and high-performance buildings.

2.2 Green building standards

The growing demand for green buildings is boosting the interest in different green building standards, rating systems, and certification schemes to help guide the building developers to achieve sustainable, high-performance and healthy buildings. This chapter discusses some of the most popular green building rating systems today.

2.2.1 LEED

Leadership in Energy and Environmental Design (LEED) is a voluntary rating system launched by the U.S. Green Building Council (USGBC) in 1998. Buildings and neighborhoods where sustainable practices and strategies are implemented can use LEED to verify their performance. LEED is designed to cover most types of buildings. Rather than being just a point system, LEED provides a framework for the project team to identify and implement practical and measurable green building solutions throughout the building life cycle. (12)

LEED is a point-based rating system in which points are awarded for buildings that meet the requirements in the following categories:

- Integrative Process
- Location and Transportation
- Sustainable Sites
- Water Efficiency
- Energy and Atmosphere
- Materials and Resources
- Indoor Environmental Quality
- Innovation
- Regional Priority

LEED has become an internationally recognized framework that is used by many building and construction projects around the world. According to the USGBC, there are LEED-certified buildings in 165 countries and territories with more than 200,000 square meters of building area that is certified every day. (12)

2.2.2 BREEAM

Building Research Establishment Environmental Assessment Methodology (BREEAM) is the first sustainability assessment scheme in the world designed for masterplan projects, infrastructure, and buildings. Launched in 1990 by the Building Research Establishment (BRE), BREEAM has become one of the most inclusive and widely accepted rating systems, setting the standard for best practices in the built environment. (13)

BREEAM focuses on the value of sustainability across a range of categories:

- Energy
- Land use and ecology
- Water
- Health and wellbeing
- Pollution
- Transport
- Materials
- Waste
- Management

Project buildings in the UK can use BREEAM as a benchmarking tool to compare their performance with other BREEAM rated buildings of similar function. It is estimated that today there are about half a million of BREEAM certified buildings and more than 2 million projects are going to be assessed. The demand from outside of the UK has also prompted BRE to create BREEAM versions for international projects, which are now present in over 70 countries around the world and are currently the most popular systems in Europe with 80% of the market share. (13)

2.2.3 DGNB

Founded in 2007 in Stuttgart, DGNB – the abbreviation for the German Sustainable Building Council in German - is building an assessment system that is based on the sustainability dimensions. It can be said that the term 'sustainability' has a wider meaning in the DGNB system than its common meaning in green building. It represents a holistic approach in which all important aspects of sustainability are considered, as the building performance is evaluated as a whole rather than just individual measures and the assessment is based on the entire life cycle of a building. (14)

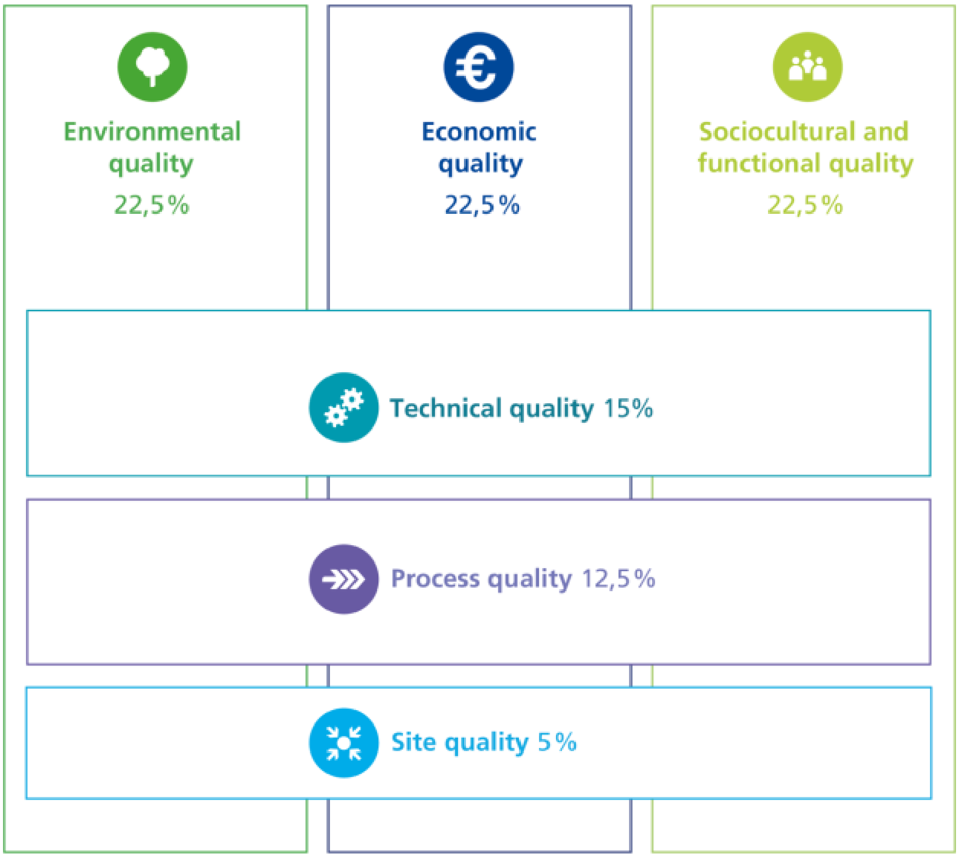

Figure 2. Basic structure of DGNB system. (44)

Besides the environmental and socio-cultural quality that are often associated with green buildings, the DGNB certification system also provides for the assessment of the economic quality of a building, as well as three other qualities: technical quality, quality of the design, construction and monitoring processes and quality of the site.

2.2.4 WELL

Launched in 2014 by the International WELL Building Institute (IWBI), the WELL Building Standard is the world's first benchmark designed to focus especially on people's health and wellness to improve sustainability. (15) WELL introduced the second version in 2018 which expands the list of concepts to 11 compared to 8 concepts in the previous version:

- Air
- Water

- Nourishment
- Light
- Movement
- Thermal Comfort
- Sound
- Materials
- Mind
- Community
- Innovation

Although still being in its fancy, WELL is changing the way buildings are being designed. Over the past few years, there has been a burst of interest in the health and wellbeing topic within the built environment. WELL is designed to bring together environmental and social elements to creating better working and living spaces. With the building occupants as the center of focus, the benefits of implementing WELL strategies are realized through happier and healthier people. As staff cost is often the biggest cost of any business, having productive and healthy employees could mean big cost saving from sick leaves and increased profits through improved productivity.

2.3 Smart buildings are the new green

2.3.1 Overview of existing definitions

Nowadays, everything – from mobile phones to cars - is called ‘smart’. But what does the term ‘smart’ mean for a building? In recent years, there has been an increase in the amount of academic and industrial publications discussing the smart building concept, but few come up with concrete definitions as to what it in reality means. These definitions often differ from each other and a few pieces of literature can address how this smart building concept can be realized and assessed. As the term ‘sustainable’, ‘smart’ is a challenging term to define and without a concrete definition, it could become a buzzword of empty meaning. In this chapter, some of the current literature working on the subject is used to identify the commonalities and new aspects of smart buildings from the academic and industrial research works.

From the academic side, Brown et al. (16) defined smart buildings are buildings designed with the occupants as the focus point, by creating an active environment where feedbacks are exchanged between the occupants and the intelligent systems, allowing effective control and management of the building. A year later, Sinopoli (17) in his publication suggested that smart building integrates technology and services systems, such as HVAC and automation systems, telecommunications, fire safety, and facility management. Kiliccote et al. (18) proposed that smart buildings are ‘conscious’ of their interaction with the grid, adjusting their energy demand in real-time to match with the signals from the energy systems through demand response and advanced controls. In 2014, Buckman & Beck (19) widened the definition of smart buildings to account for four aspects: intelligence, enterprise, control, and materials and construction. They are convinced that adaptability, not reactivity, is the core of smart buildings to achieve energy efficiency, resilience, user comfort, and satisfaction.

From the industry side, EuroACE (20), building on the definition of nZEBs, described smart buildings as functional, highly energy-efficient, grid-connected buildings that utilizing advanced technologies to empower the owners and users with reliable data to make informed decisions about energy consumption. 'Digitally connected structures' that reduce operational costs, improve user experience, enhance productivity and minimize physical and cybersecurity risks through building automation optimization and smart space management, is what smart buildings are, according to Deloitte firm. (21) Another big firm Ernst and Young (22), often known as EY, gave their take on smart buildings, saying that truly smart buildings are not about the technologies but about how well they can respond of the present needs of the users and the long-term needs of the owners and investors. This is measured by how well the systems in the building communicate and work together, collecting and analyzing data to increase building performance. Siemens (23) mentioned that business success and user satisfaction are the main contributions of smart buildings by actively and continuously learning and adapting. From the high-rise point of view, CTBUH (24) also shared a similar view, that smart buildings collect and act on data to achieve comfort, productivity, health, and sustainability.

Having explored a range of smart building definitions, including some of those mentioned above, BPIE (25) proposed a definition of a smart building from a European vision: a very energy efficient building with low energy demand met by on-site generation and renewable-based district energy systems, with three main goals:

1. to stabilize and rapidly decarbonize the energy system through energy storage solutions and demand-side flexibility strategies;
2. to empower its users with control over the energy flows,
3. to monitor and respond to user demands in terms of comfort, health, indoor air quality, safety as well as operational requirements.

2.3.2 Smart building from EU perspective

The Energy Performance of Buildings Directive (EPBD) is one of the EU's main tool to legislate energy performance of buildings. This Directive has been enforced since 2010 and requires all Member States to set out energy efficiency requirements in their national building codes. The revised 2018 EPBD (26) includes amendments to the 2010 version and introduces new strategies following the adoption of the "Clean Energy for All European" package in 2016. One of the key strategies is promoting smart building technologies through the introduction of the smart readiness indicator (SRI).

Smart readiness indicator (SRI)

Under Article 8, sections 10-11 and Annex Ia of the revised EPBD, the European Commission is instructed to develop a common European scheme for rating the smart readiness of buildings by the end of 2019. The main purposes of the scheme are to stimulate market uptake of smart technologies, to encourage the use of information and communication technology (ICT) and smart energy solutions to ensure efficient operation of buildings and to raise awareness of the benefits of smart technologies on buildings and the building users. According to the revised EPBD, the rating scheme could be used to assess the capabilities of a building to adapt to the needs of the building users and the power grid, with 3 key functionalities for the building technical systems:

1. Ability to maintain energy performance and normal operation while increasing the utilization of renewable energy sources,

2. Ability to adapt in response to the user needs and maintain a good healthy indoor environment,
3. Ability to be flexible in terms of electrical demand to the grid.

A working group was formed by the European Commission Directorate-General for Energy (DG ENERGY) in early 2017 to carry out the study and development of the SRI, from which the first technical study was completed in August 2018 and the second study's interim report was released in July 2019, which provides further information to the methodology proposed in the first study. In general, the proposed SRI methodology contains a catalog of smart ready services and levels of functionalities that can be inspected for an assessed building. If a service is present in the building, it can then be assessed based on its functionality level, or 'smartness' level, and then a score is given. Higher functionality levels or smarter services results in higher SRI score.

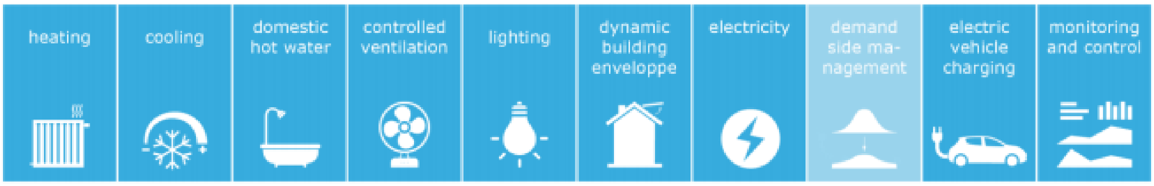

Figure 3. Domains in the SRI. (27)

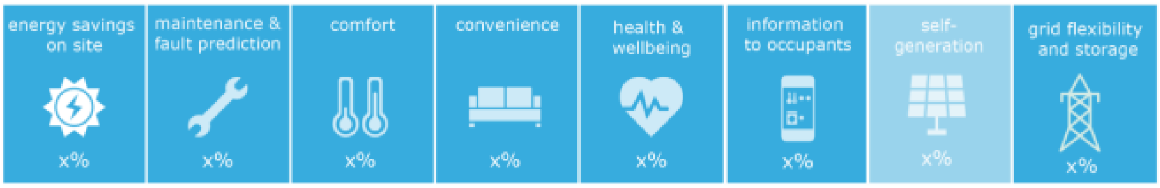

Figure 4. Impact criteria in the SRI. (27)

The smart ready services are divided into 10 domains shown in Figure 3, and their levels of functionality result in impact scores in 8 impact types shown in Figure 4. The 'demand-side management' domain and 'self-generation' impacts are greyed out because their services have been integrated into other domains and impact groups, according to the second technical study. (27)

IEA EBC Annex 67 Energy Flexible Buildings

The Energy in Buildings and Communities (EBC) is a program established by the International Energy Agency (IEA) to coordinate research projects related to energy prediction and efficiency measures within the built environment. The Annex 67 "Energy Flexible Buildings" of the EBC focuses on energy flexibility in buildings and its role in facilitating the future energy systems that are foreseen to be largely renewable energy-based. As renewable energy sources are intermittent and weather dependent, their large deployment may serious destabilize the grids. Therefore, buildings as one of the main consumers of grid electricity must be energy-flexible to adjust their energy demand according to the grid requirements and other factors such as user needs and climate conditions. (28)

In the position paper published in 2017, Annex 67 proposed a different view of the method of the SRI. According to this paper, while the SRI is based on a qualitative approach to defining the "smartness" of a building, the approach of Annex 67 is through quantitative and physical Energy Flexibility indicators. By using these indicators, the Annex argues that this method supports decision making with a data-driven and simulation-based approach. However, it also acknowledges that energy flexibility is not the only indicator of how smart buildings should be, but rather the way that they interact with the occupants, the grid and other boundary conditions. (28)

The Energy Flexibility indicators from the Annex 67 have not been published but there is already an increasing amount of research on the energy flexibility indicators for buildings, some of which are also studied by the Annex.

2.4 Concluding remarks

Looking at what is happening in the green building and smart building sectors, it is clear that they are both very wide concepts that take into account different aspects concerning sustainability, building occupants and energy. To define the smart and sustainable building (SSB) concept, it is necessary to have a holistic view of all the important aspects. A definition of what is an SSB is proposed based on the gathered literature, which includes:

1. A building that, over its entire life cycle, has a net positive impact on the natural environment and the planet.
2. A building that delivers the best user experience for the occupants - by intelligently leveraging data collection to effectively manage its systems to enhance comfort, productivity, health, and sustainability.
3. A building that supports and accelerates the decarbonization of the energy systems through energy efficiency measures, use of clean renewable energy and demand-side flexibility.

Despite covering a wide area of topics, green buildings and smart buildings also share common aspects such as promoting energy efficiency, increasing uptake of renewable energy and shifting the attention to occupant health and wellbeing. Figure 5 demonstrates the identified features of smart buildings and green buildings.

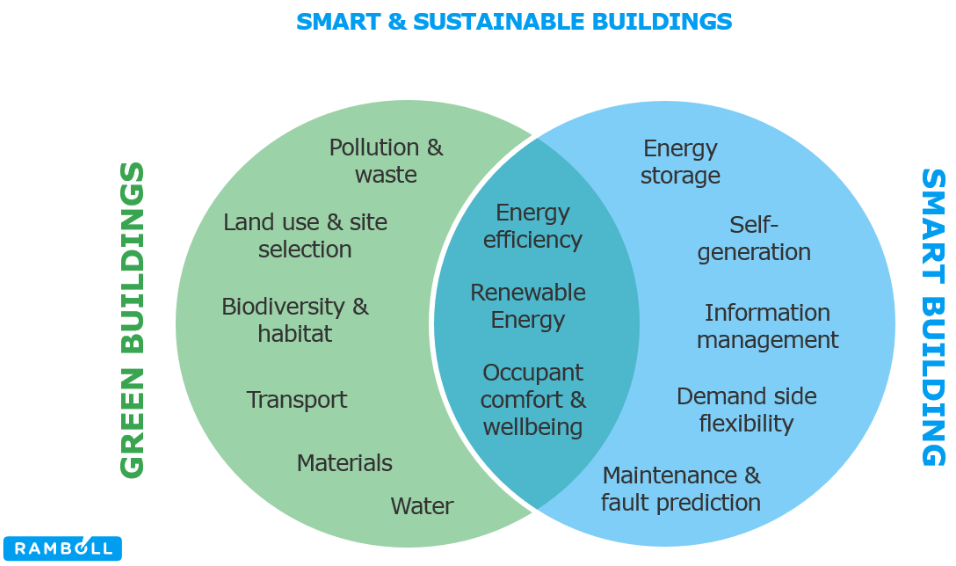

Figure 5. Identified features of smart and sustainable buildings

From the literature research, it can be said that green building standards, in general, have a strong focus on green construction but not on how buildings can adapt to the user's needs and interact with the energy system. Smart building initiatives, on the other hand, do not address the impacts of buildings on the environment and the planet. Thus, there is a need to develop a building assessment method for buildings that are smart and achieve their sustainability goals. The following chapter discusses the development of a smartness and sustainability index for buildings that collect indicators from the existing frameworks:

- Green building standards LEED, BREEAM and DGNB for the indicators that are related to green building design and construction,
- WELL building standard for the occupant-focused indicators,
- Energy flexibility indicators proposed by the Annex 67.

3 Smartness and sustainability index

3.1 Overview of the framework structure

In total, 23 indicators have been selected to form the basis of the Building Assessment for Smartness and Sustainability (BASS) Index, as shown in Table 1. Each indicator represents a part of a holistic view of a building's performance in three dimensions: Green Construction, Health & Wellbeing, and Energy Flexibility. Each of these dimensions provides a separate view of performance and when combined provide a holistic view of a smart and sustainable building. Within each dimension, some categories focus on more specific areas of performance. This collection of indicators for Smart and Sustainable Buildings provides a methodology on how to benchmark the building performance from the collected data or information. Since there are many different criteria for different building types and building life-cycle stages within the existing frameworks, the BASS system has been developed to assess the smartness and sustainability mainly on a new office building.

A Likert scale of 1-5 is used for benchmarking purposes, with level 1 being the lowest performance and level 5 being the top performance. To fit the criteria of the existing frameworks into the BASS system, the general principle is that the minimum performance criteria are given a score of 3 and the higher performance criteria receive a score of 4. Anything less than the minimum requirement is scored 1 and anything better than the exemplary performance gets the highest score of 5. Sometimes exceptions have to be made, however, the general idea is that a score of 3 represents the building achieves minimum performance as states in the existing frameworks. Exceeding or not meeting the minimum requirements are then scored accordingly.

Table 1. Structure of the BASS system

Dimension	Category	No.	Indicator name
Green construction	Air pollution	KPI1	NOx emissions
		KPI2	Refrigerant impacts
	Materials & waste	KPI3	Life cycle impact reduction
		KPI4	Construction and demolition waste
	Ecology	KPI5	Land use
	Climate, water & energy	KPI6	GHG emissions from energy use
		KPI7	Renewable energy
		KPI8	Water use intensity
	Transport	KPI9	Public transport accessibility
		KPI10	Bicycle storage availability
	Flexibility & adaptability	KPI11	Space efficiency
Health & Wellbeing	Indoor Environment Quality	KPI12	Indoor air quality
		KPI13	Daylight exposure
		KPI14	Thermal comfort
		KPI15	Background noise
	Wellbeing	KPI16	Water quality
		KPI17	Fruit and vegetable availability
		KPI18	Physical and visual ergonomics
		KPI19	Access to nature
Energy Flexibility	Demand-side flexibility	KPI20	Flexibility factor
	Load matching & grid interaction	KPI21	Self-generation
		KPI22	Self-consumption
		KPI23	Grid independence

These indicators have been selected to provide with a guideline on how to collect data systematically so that the building performance can be assessed and benchmarked, helping buildings to:

- Become a more sustainable building,
- Becoming a healthier building,
- Becoming a more energy flexible building.

The results of these indicators allow the comparison of different buildings and provide insights into best practices and technologies that add value for the buildings, the users and the societies.

3.2 Criteria for indicator selection

Scanning through the existing indicators from the literature results in a long list of around 150 available indicators, which are quite many for this scope of this thesis work. To come up with a shortlist of indicators for the BASS system, a set of criteria for selection is needed. The criteria, based on the CIVITAS framework (29), are listed below:

- Relevance: each indicator should be relevant to the theme of smart and sustainable and should have significant importance to the objectives of the system. Indicators that are influenced by other factors than the implementation of assessment for buildings are not suited.
- Completeness: the set of indicators aims to cover the most important aspects of smartness and sustainability in the buildings. The indicators are selected according to the themes identified: green construction, occupant health and wellbeing, and energy flexibility.
- Availability: the data should be available or relatively easy to be collected for the indicators.
- Measurability: the selected indicators must be measurable, meaning that they are preferably quantitative indicators that have calculation methodology.
- Reliability: the indicators should be chosen from reliable sources (existing frameworks).
- Familiarity: the indicators should be easy to understand for the potential users.
- Non-redundancy: the indicators should be selected so that no two indicators should measure the same subject.
- Independence: the idea is that small changes in one indicator do not affect the other indicators. However, since many topics within the themes are closely related, some exceptions must be made.

The long list of indicators derived from existing frameworks can be obtained from the author.

3.3 Indicators for smart and sustainable buildings

This section provides more detailed information on the selected indicators for Smart and Sustainable Buildings. Each indicator is presented with the following headers:

- Indicator number and name for ease of identification
- A short description of the aim of the indicator
- A brief background of the indicator and its impacts
- The benchmarking developed for the BASS system based on the existing frameworks
- The calculation methodology provided by the existing frameworks

3.3.1 Air pollution

Poor air quality is a global health hazard that kills an estimated 7 million people worldwide every year, according to the World Health Organization (WHO). Air pollution is responsible for a third of all deaths from stroke, lung cancer, and heart disease. In many parts of the world, especially in low- and middle-income countries, most of the population is still exposed every day to poor air quality that exceeds the WHO's guideline levels multiple times over, representing a major issue affecting the people's health. (30)

The purpose of this category is to reduce air pollution associated with the operation of building heating and cooling systems. Two indicators have been identified and selected for this category: NOx emissions (KPI 1) and Impacts of refrigerants (KPI 2).

KPI 1 – NOX EMISSIONS

Definition

This indicator aims to help reduce NOx emissions associated with buildings by encouraging the use of low emission heat sources for space heating and domestic hot water.

Background

NOx emissions, mainly talking about nitric oxide (NO) and nitrogen dioxide (NO2), is produced from the combustion of fuels, especially at high temperature. Nitrogen, when released from the combustion process, combines with oxygen atoms to create nitric oxide. Nitric oxide then further combines with more oxygen to create nitrogen oxide. Both are referred to as NOx gases that when released into the atmosphere can create smog and acid rain, causing the formation of fine particles (PM) and ground-level ozone, which have detrimental health effects on the people. (31)

Reference standard

Space heating and domestic hot water heating are the main sources of buildings' NOx emissions. According to BREEAM technical manual (32), all building types other than industrial buildings must meet minimum NOx emission levels according to Table 2. The emissions are determined from the measurements, on a dry basis at 0% excess O_2 and under normal operating conditions, of the plant that provides the building's space heating and hot water demand.

Table 2. BREEAM's NOx emission credits

NOx emission levels for heating and hot water (mg/kWh)	Credits
≤ 56 mg/kWh	1
≤ 40 mg/kWh	2

For industrial buildings, the NOx emissions are assessed separately for the office part and the operational part of the building, so that each part can achieve one credit each if its level of NOx emissions is less than or equal to 56 mg/kWh.

Benchmarking
The benchmarking levels of the BASS system are divided based on BREEAM's reference values is shown in Table 3 below:

Table 3. Benchmarking of KPI 1 – NOx emissions

NOx emission levels for heating and hot water (mg/kWh)	Score
>72	1
57-72	2
41-56	3
21-40	4
0-20	5

Methodology
The NOx emissions for combined heat and power (CHP) systems can be calculated using Equation 1:

$$X = A \times \left(\frac{B}{B + C}\right) \tag{1}$$

where:
X is NOx emissions per unit of heat generated (mg/kWh heat)
A is NOx emissions per unit of fuel input (mg/kWh fuel input)
B is heat output (kW)
C is electrical output (kW)

Where multiple systems operating in conjunction are specified, an average NOx emissions value should be calculated using Equation 2:

$$NOx\ avg = \left(N1 \times \left(\frac{H1}{HT}\right) + N2 \times \left(\frac{H2}{HT}\right)\right) \ldots + \left(Nn \times \left(\frac{Hn}{HT}\right)\right) \tag{2}$$

where:
NOx avg is average NOx of all sources
N1 is NOx emissions rate for source 1
N2 is NOx emissions rate for source 2
Nn is NOx emissions rate for source 2
HT is total heat output from all sources
H1 is heat output from source 1
H2 is heat output from source 2
Hn is heat output from source n

KP2 – REFRIGERANT IMPACTS

Definition
This indicator aims to diminish greenhouse gas emissions originated from the leakage of refrigerants used in the building's heating and cooling system.

Background
Refrigerants are commonly used in buildings over the world for heating, cooling and refrigeration purposes thanks to their favorable thermodynamic properties. However, it is a known fact that most of the refrigerants are extremely harmful to the people and the environment. In addition to being toxic or explosive, refrigerants have a negative impact on the stratospheric ozone layer. Since 1989, chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC) have been phased out under the Montreal Protocol as they were discovered to be ozone-depleting refrigerants. In 2016, the Parties to the Montreal Protocol met in Kigali, Rwanda to phase-down hydrofluorocarbons (HFC). HFCs are commonly used alternatives to CFCs and HCFCs. While not dangerous to the ozone layer, HFCs are substances that have very high global warming potentials. (33,34)

Reference standard
BREEAM's credit *Impacts of Refrigerants* awards credits through two pathways: buildings that use no refrigerants at all and buildings with systems that use refrigerants at the Direct Effect Life Cycle CO_2 equivalent emissions (DELC CO_{2e}) according to Table 4.

Table 4. BREEAM's Impacts of Refrigerants credits

DELC CO_{2e} ($kgCO_{2e}$ /kW cooling or heating capacity)	Credits
≤ 1000	1
≤ 100	2

For a building that does require the use of refrigerants, the requirements of standards EN 378:2008+A2:2012 (75) (parts 2 and3), ISO 5149:2014 or the Institute of Refrigeration Ammonia Refrigeration Systems Code of Practice must be met as a prerequisite. In addition, the use of refrigerants with zero ODP and having refrigerant leak detection and management strategies in place earn the building two more credits. (32)

Benchmarking
The benchmarking levels are divided based on BREEAM's reference values is shown in Table 5 below:

Table 5. Benchmarking of KPI 2 – Impacts of refrigerants

DELC CO_{2e} ($kgCO_{2e}$ /kW cooling or heating capacity)	Score
>1000	1
700-1000	2
400-699	3
100-399	4
0-99	5

A mandatory condition for this benchmarking is that the building must not use CFC refrigerants, as they have been banned under the Montreal Protocol since 2010. (34)

Methodology
The DELC CO_{2e} can be calculated using Equation 3:

$$\frac{[RLO + RLSR] \times GWP}{CC} \tag{3}$$

Refrigerant loss operational (RLO) is calculated using Equation 4:

$$RLO = (Ref_{charge} \times Sys_{op-life} \times (L1 + L2 + S1 + S2))/100 \tag{4}$$

Refrigerant loss system retirement (RLSR) is calculated using Equation 5:

$$RLSR = Ref_{charge} \times (1 - Ref_{RecEff}/100) \tag{5}$$

where:
Ref_{charge} is refrigerant charge (kg)
$Sys_{op-life}$ is system operational lifetime (years)
Ref_{RecEff} is refrigerant recovery efficiency factor (%)
L1 is annual leakage rate (% refrigerant charge)
L2 is annual purge release factor (% refrigerant charge)
S1 is annual service release (% refrigerant charge)
S2 is probability factor for catastrophic failure (% refrigerant charge loss/year)
GWP is Global Warming Potential of refrigerant
CC is cooling or heating capacity (kW)

3.3.2 Materials and waste

This category focuses on minimizing the embodied impacts of building materials throughout their entire life cycle of extraction, manufacturing, transport, installation, maintenance, and disposal. It also encourages the uptake of a circular economy approach by source reduction, reuse, recycling and converting waste to useful purposes such as energy. Two indicators have been identified and selected: Life-cycle impact reduction (KPI 3) and Construction and demolition waste (KPI 4).

KPI 3 – LIFE CYCLE IMPACT REDUCTION

Definition
This indicator aims to promote the life cycle thinking approach through the utilization of building life cycle assessment (LCA) tools that consider the environmental impacts (including embodied carbon) of building materials from cradle-to-grave.

Background
Buildings, big or small, at all life-cycle stages have an impact on the environment. According to the 2011 'The Roadmap to a Resource Efficient Europe (RERM)' (35), better building construction could reduce 42% of final energy consumption, equivalent to about 35% of total GHG emissions, cutting up to half of the need to extract raw materials and a third of water consumption in some areas. A robust LCA tool can provide valuable information about the life cycle impacts of different building materials, allowing projects to make informed decisions that have positive impacts on the environment, the people and the communities.

Reference standard
A building can earn up to 4 credits in LEED (36) for carrying out an LCA study of the building's structure and enclosure, following one of the paths shown in Table 6.

Table 6. LEED's Building Life-Cycle Impact Reduction credits

Whole building life cycle assessment pathways	Credits
Conduct an LCA of the project's structure and enclosure	1
Minimum 5% reduction, in at least 3 categories, one of which is GWP	2
Minimum 10% reduction, in at least 3 categories, one of which is GWP	3
Minimum 20% reduction of GWP and 10% reduction in two other categories	4

The impact categories mentioned are: global warming potential, depletion of the stratospheric ozone layer, acidification of land and water sources, eutrophication, the formation of tropospheric ozone and depletion of nonrenewable energy resources

Benchmarking
To simplify the criteria, only the global warming potential is considered for benchmarking as it has the most significant importance. The threshold levels are divided as shown in Table 7 below:

Table 7. Benchmarking of KPI 3 – Life cycle assessment

Percentage of greenhouse gas emissions reduction over baseline	Score
<5	1
5-9	2
10-14	3
15-20	4
>20	5

Methodology
This indicator is carried out by conducting a building life cycle assessment using a robust LCA tool, meaning that it should contain sets of ISO 14044 compliant data and calculations in the background which users are not allowed to modify. It should also be able to produce the results that are required for the entire calculation period of the assessment. One example of LCA tools is the OneClick LCA by Finnish company Bionova Ltd.

The general guideline for conducting the LCA is as followed (36):

1. **Establish the baseline building to compare with design alternative**: the building envelope such as walls, roofs, and floors are defined according to ASHRAE 90.1-

2010 Appendix G for the climate zone of the building's specific location. The model should not include technical systems such as electrical, mechanical, fire protection, plumbing, elevators. Parking structures are included, but not parking lots.
2. **Identify the design alternative with lesser impacts**: by modifying the baseline building but keeping the following parameters: building function, site boundary, size (gross floor area), orientation, location, and operating energy performance.
3. **Input the baseline and design buildings into the chosen LCA tool for comparison**: the entire building structure and enclosure must be taken into account from design to demolition for assumed 60-year service life.

Some examples of design alternatives for analyzing, including but not limited to:
- Evaluate different structures, such as load-bearing walls and columns
- Optimize structural design, such as column spacing and slab depth
- Compare the environmental impacts of building footprint and shape

KPI 4 – CONSTRUCTION AND DEMOLITION WASTE

Definition
This indicator aims to reduce construction and demolition waste disposed of in landfills and incineration facilities.

Background
In the United States, about 40 percent of the total solid waste is from construction and demolition processes. (37) This figure is about 25% for the European Union. (38) Earth Overshoot Day shows that humans have used more resources than Planet Earth can regenerate. (39) Therefore, by keeping the materials away from landfills, it promotes recycling, keeping valuable natural resources in longer use and helps prevent pollution to the ground and water.

Reference standard
In BREEAM, the requirements for waste diversion rates are specified depending on the national construction and demolition waste recovery rate, where the building is located. The requirements are for the national waste recovery rate either less than 50% or 50% and higher. However, to keep it simple for benchmarking purposes, it is assumed that the rate is 50%. BREEAM target rates for diversion from landfill is shown in Table 8.

Table 8. BREEAM's Construction waste management credits

Type of waste	One credit	Two credits
Construction waste	≥ 60% (10% improvement over national rate)	≥ 85% (35% improvement over national rate)
Demolition waste	≥ 60% (10% improvement over national rate)	≥ 95 % of total waste is diverted from landfill

Benchmarking
The benchmarking uses BREEAM target rates for diversion from landfills as reference values, as shown in Table 9.

Table 9. Benchmarking of KPI 4 – Construction and demolition waste

Percentage of construction (and/or demolition) diverted	Score
<50	1
50-59	2
60-84	3
85-94	4
95-100	5

Methodology
The percentage of construction and demolition waste diverted from landfills and incineration facilities is calculated using Equation 6:

$$\%\,Waste\ diverted = \frac{Total\ amount\ of\ waste\ diverted}{Total\ amount\ of\ waste\ created} \times 100\% \qquad (6)$$

Materials diverted away from landfills and incineration places can be recycled or recovered through a variety of methods, such as reuse directly on-site, reuse on other sites, salvage or reclaim for other reusing purposes, return to the supplier if possible or recover and sort by waste management firms for recycling.

3.3.3 Ecology

This category encourages sustainable use of land, protecting the habitat and improve the biodiversity on and around the building's site. One indicator, Land use (KPI 5), has been identified and selected. Another indicator that could have been included was the biodiversity index, but unfortunately, the author did not have information about DGNB's calculation method for biodiversity index. The indicator is 'reserved' for future development.

KPI 5 – LAND USE

Definition
This indicator aims to encourage the use of land that has been previously occupied or developed so that undisturbed land can be avoided.

Background
Sustainable site selection is one of the first strategies that can be done to lessen the environmental impacts of a building project. By limiting the building's footprint to previously developed and occupied land, ecologically sensitive land is preserved for species and provides habitat to support biodiversity, which benefits the people and the environment. Building on a previously developed site also encourages the reuse of existing built infrastructure and neighborhoods.

Reference standard

BREEAM awards credits based on the percentage of the assessed building's footprint on a site which has been occupied before by other buildings or infrastructures (see Table 10).

Table 10. BREEAM's Previously occupied land credits

Percentage of the proposed development's footprint on previously developed land (PDL)	Credits
75%	1
95%	2

Benchmarking

Benchmarking levels of KPI 5 are shown in Table 11.

Table 11. Benchmarking of KPI 5 – Land use

Percentage of the development's footprint on PDL	Score
<65	1
65-74	2
75-84	3
85-94	4
95-100	5

Methodology

The percentage of the development's footprint is on an area of land which has previously been developed or occupied is calculated using Equation 7:

$$\% \, PDL = \frac{Total \; building's \; footprint \; on \; PDL}{Total \; building's \; footprint} \times 100\% \tag{7}$$

3.3.4 Climate, water and energy

This category focuses on some of the biggest issues that humanity is currently facing climate change impacts related to energy use and water scarcity. Building energy efficiency is perhaps one of the most often talked about topic when it comes to sustainability in the built environment, while droughts are affecting the lives of millions of people around the world. The selected KPIs are GHG emissions from energy use (KPI 6), Renewable energy (KPI 7) and Water use intensity (KPI 8).

KPI 6- GHG EMISSIONS FROM ENERGY USE

Definition

This indicator aims to reduce GHG emissions from excessive energy use by achieving high energy efficiency for the building and its systems.

Background
Accounting for nearly 40% of the total energy used today (1), it is without questions that buildings are significant contributors to energy-related climate change problems. Achieving high energy performance requires a holistic approach, taking into consideration passive and active design strategies, increasing the use of non-fossil fuel energy and ensuring that all building systems operate effectively and efficiently.

Reference standard
In previous versions of LEED, credits for whole-building energy simulation options are determined by calculating the percentage of improvement in terms of energy costs between the baseline and proposed buildings. However, in the latest version 4.1, the amount of credits is divided equally for improvements in energy costs and GHG emission reduction. This is a welcoming approach from LEED as it now addressing the importance of reducing GHG emissions from building energy use, which is an urgent action that needs to be taken to keep global warming within the 1.5C increase.

Benchmarking
This indicator is benchmarked using the GHG emission reduction part of LEED, which is shown in Table 12.

Table 12. Benchmarking of KPI 6 – GHG emissions from energy use

Percentage of GHG emissions reduction associated with building energy use	**Score**
5-19	1
20-39	2
40-59	3
60-79	4
80-100	5

Any building achieves less than 5% improvement will not be considered for this indicator.

Methodology
This indicator requires building energy simulation to be carried out in compliance with the LEED energy simulation modeling protocol. In general, a proposed model is constructed based on the actual building design, and a baseline model which is created from the proposed model following ASHRAE standard 90.1-2016, Appendix G modeling requirements.

After the energy models have been completed, the following metrics need to be calculated from the energy modeling results: Performance Cost Index (PCI) using Equation 8 and target Performance Cost Index (PCI_t) using Equation 9.

$$PCI = \frac{Proposed\ building\ energy\ consumption}{Baseline\ building\ energy\ consumption} \tag{8}$$

$$PCIt = \frac{[\text{BBUEC} + \text{BPF x BBREC}]}{\text{BBP}} \tag{9}$$

where:
BBUEC is baseline GHG emissions from unregulated energy
BBREC is baseline GHG emissions from regulated energy
BPF is building performance factor
BBP is baseline building performance (BBUEC + BBREC)

The building performance factor can be found in ASHRAE standard 90.1-2016, Appendix G, Table 4.2.1.1. Table 13 is an extract from that table for projects in climate zone 7.

Table 13. ASHRAE 90.1-2016 Building Performance Factor

Building type	**Climate zone 7**
Hospital	0.56
Hotel	0.57
Office	0.57
Retail	0.53
School	0.47
Warehouse	0.67
Others	0.53

To determine the number of credits can be awarded, the percentage of GHG emission reduction over baseline is calculated using Equation 10:

$$\%\, improvement = 1 - \frac{PCI}{PCIt} \times 100\% \tag{10}$$

KPI 7 - RENEWABLE ENERGY

Definition
This indicator aims to reduce greenhouse gas emissions by increasing the self-generation and use of renewable energy on the building's site.

Background
By producing renewable energy on-site, buildings are protected from the risks of the energy market's price volatility, reliance on the grid and energy transmission loss. Ultimately, renewable energy production contributes to reducing greenhouse gas emissions and lower the demand for imported energy.

Reference standard

LEED provides five different strategies for renewable energy procurement, including on-site and off-site renewable generation, which can be combined to achieve a total of 5 credits. Table 14 below presents the credit thresholds for on-site renewable energy generation strategy.

Table 14. LEED's Renewable Energy credits

Percentage of on-site renewable energy	Credits
2%	1
5%	2
10%	3
20%	4
40%	5
60%	EP

Benchmarking

To make it easier for benchmarking, only on-site renewable energy is considered for this indicator, as shown in Table 15.

Table 15. Benchmarking of KPI 7 – Renewable energy

Percentage of GHG emissions reduction associated with building energy use	Score
< 2	1
2-19	2
20-39	3
40-59	4
60-100	5

Methodology

To calculate the percentage of renewable energy produced by the building, the following Equation 11 is used:

$$\%\ Renewable\ energy = \frac{Renewable\ energy\ annual\ production}{Total\ building\ annual\ energy\ consumption} \times 100\% \tag{11}$$

Sources that are considered as renewable energy in LEED include the following:

- Photovoltaic
- Solar thermal
- Wind
- Biofuel
- Low-impact hydroelectricity
- Wave and tidal energy
- Geothermal energy

Exceptions are geothermal energy used in conjunction with vapor compression cycles (i.e. ground-source heat pump) and biofuels from solid waste, forest biomass, and contaminated wood.

KPI 8 - WATER USE INTENSITY

Definition
This indicator aims to reduce indoor water consumption.

Background
Water conservation is important because only 3% of Earth's water is freshwater, and of that, about 70% is trapped in glaciers. (40) In more than half of the big European cities, groundwater is being used faster than it can be replenished. (41) Using water efficiently in buildings helps reduce the building's operational costs and the energy needed for water treatment and transport.

Reference standard
To achieve water use reduction credits in LEED, indoor potable water consumption must be reduced by at least 20% from the baseline water consumption, which is calculated by using a set of flow or flush rates for the water fixtures designed or installed in the building. The credits are then awarded according to the levels in Table 16.

Table 16. LEED's Indoor Water Use Reduction credits

Percentage of water consumption reduction over the baseline	Credits
20%	Minimum requirement
25%	1
30%	2
35%	3
40%	4
45%	5
50%	6

Benchmarking
Benchmarking levels of this indicator are shown in Table 17.

Table 17. Benchmarking of KPI 8 - Water use intensity

Percentage of indoor water consumption improvement	Score
<20	1
20-29	2
30-39	3
40-49	4
≥ 50	5

Methodology
Equation 12 is used for indoor water use reduction calculation:

$$\begin{aligned} & \textit{Daily water use for each fixture} \\ & \quad = \textit{Fixture flush or flow rate} \times \textit{Duration of use} \\ & \quad \times \textit{Users} \times \textit{Uses per person per day} \end{aligned} \tag{12}$$

Equation 13 is used to calculate the improvement percentage of indoor water use reduction:

$$\%\ \textit{improvement} = \left\{\frac{\textit{Baseline volume} - \textit{Design volume}}{\textit{Baseline volume}}\right\} \times 100 \tag{13}$$

3.3.5 Transport

This category focuses on encouraging alternative transportation options from the building design's point of view. Two indicators Public transport accessibility (KPI 9) and Bicycle storage availability (KPI 10) are included in this category. The former rewards location of the building site with good access to the local public transport network while the latter encourages the use of bicycles for commuting. Both indicators intend to reduce emissions from the use of private fossil-fueled vehicles.

KPI 9 – PUBLIC TRANSPORT ACCESSIBILITY

Definition
This indicator demonstrates the proximity to frequent public transport from the building.

Background
In 2016, the transport sector accounts for 27% of the EU's total GHG emissions. Of that, 72% comes from road transport. The location of the building influences how people commute. Buildings situated in the proximity of existing transport infrastructure encourage

people to use more public transport, hence reducing the use of private vehicles and emissions. (42)

Reference standard
BREEAM uses accessibility index (AI) as a measure of the accessibility and density of the public transport network from the assessed building. The AI index is influenced by the proximity, diversity, and frequency of public transport services. Credits are awarded for office building type the AI score according to Table 18.

Table 18. BREEAM's Public transport accessibility credits

Accessibility Index	Credit
≥ 2	1
≥ 4	2
≥ 8	3

Benchmarking
Table 19 presents the benchmarking of the building's public transport accessibility index.

Table 19. Benchmarking of KPI 9 – Public transport accessibility

Accessibility Index	Score
< 2	1
2 – 3.9	2
4 – 5.9	3
6 – 7.9	4
≥ 8	5

Methodology
BREEAM's Tra01 tool is used to calculate the AI score. For the calculation, a list of compliant transport nodes and the average number of services for each node need to be identified. According to BREEAM, a compliant node is any bus stop within 650m and any train station within 1000m of the building's main entrance. The distance should be measured using a safe pedestrian route connecting the node to the entrance. The average number of services per hour is determined by collecting the number of services serving the node during the building's typical operating hours and the total number of hours during the building's normal operating.

The frequency of public transport is calculated using Equation 14 below:

$$Frequency\ of\ public\ transport = \frac{Number\ of\ services\ during\ operating\ hours}{Total\ building's\ operating\ hours} \tag{14}$$

KPI 10 – BICYCLE STORAGE AVAILABILITY

Definition
This indicator aims to promote the use of bicycles as a mode of transport and subsequently improve public health.

Background
Riding bicycle to commute offers a wide range of benefits: it is cheap, it produces no CO2 emissions and it brings many health benefits. According to researchers from the University of Glasgow (43), people who cycle to work have 46% lower risk of developing from cardiovascular disease and 52% lower risk of dying from it. They also have 45% lower risk of developing cancer and 40% lower risk of cancer-related death. Buildings can support bicycling by providing good facilities for bicycle storage so that it is convenient for the occupants to ride to and from the buildings.

Reference standard
Bicycle storage is separated as short-term bicycle storage and long-term bicycle storage in LEED. Short-term storage is for building visitors, while long-term storage is for the regular occupants. The amount of storage is calculated based on the estimated number of visitors and regular occupants of the building.

Benchmarking
For benchmarking purposes, the bicycle storage defined here is long-term type and the amount is calculated according to the number of regular occupants, as shown in Table 20.

Table 20. Benchmarking of KPI 10 – Bicycle storage availability

Percentage of bicycle storage provided	Score
<5	1
5-9	2
10-14	3
15-19	4
≥ 20	5

Methodology
The amount of bicycle storage required is calculated using Equation 15:

$$\%\ bicycle\ storage = \frac{Number\ of\ bicycle\ storage}{Number\ of\ regular\ building\ occupants} \qquad (15)$$

3.3.6 Flexibility & adaptability

This category focuses on the ability of buildings to adapt or convert for other purposes as the demands change. In the light of social and demographic changes such as Work 4.0, Industry 4.0 and digitalization, this becomes an increasingly important feature of buildings that building developers and owners need to consider for the future. Indicator Space efficiency (KPI 11) has been identified in this category.

KPI 11 – SPACE EFFICIENCY

Definition
This criterion aims at making the design of buildings as flexible as possible to maximize the potential for conversion.

Background
The development of technology and society requires highly efficient, flexible and adaptable buildings. Buildings that provide ease of adaptation to the users' needs to raise user satisfaction, extending the building lifespan and saving money for the owners. As a result, the risk of vacancy is minimized.

Reference standard
DGNB's *Flexibility and adaptability* credit evaluate the building's flexibility and adaptability based on the following features (44):

- Space efficiency
- Ceiling height
- Depth of floor plan
- Vertical access
- Floor layout
- Structure
- Building services

Of these features, space efficiency can be quantified as shown in Table 21. In economic terms, space efficiency is the ratio of usable and rentable space to the total building area.

Table 21. DGNB's Flexibility and adaptability credits

Space efficiency factor	Points
> 0.48	1
0.60	5
0.75	10

Benchmarking
Space efficiency factor benchmarking is listed in Table 22 below.

Table 22. Benchmarking of KPI 11 – Space efficiency factor

Space efficiency factor	Score
<0.48	1
0.48-0.59	2
0.60-0.67	3
0.68-0.74	4
≥ 75	5

Methodology
According to DGNB (44), the space efficiency factor (SEF) is calculated using Equation 16:

$$SEF = \frac{UA}{GFA} \quad (16)$$

where:
UA is usable floor area (m^2)
GFA is gross floor area (m^2)

Both UA and GFA definitions are in accordance with ISO 9836:1992, in which UA represents the part of the net floor area that is used for building's purpose excluding corridors, and GFA is the total of the floor areas, measured from the exterior of external walls and the centerline of all walls that separate the building from any adjoining buildings. The space efficiency is not without limits, meaning that the areas of working spaces and corridors must be according to the legal requirements.

3.3.7 Indoor environment quality

This category focuses on improving the quality of the indoor environment for the occupants. As people spend 90% of their time indoors, it is vitally important that good indoor conditions are maintained. Health and comfort of building occupants are ensured, as well as increased productivity, reduced sick-building syndrome, and improved building value are some of the benefits of high-quality indoor environment Selected from the existing frameworks, the followings are some of the most fundamental performance-based indicators that are included in this category: Indoor air quality (KPI 12), Daylight exposure (KPI 13), Thermal comfort (KPI 14) and Background noise (KPI 15).

KPI 12 – INDOOR AIR QUALITY

Definition
This indicator aims to promote the monitoring of indoor air quality.

Background

The indoor air quality of a building affects everyone who lives and works in it. Many different factors can worsen the indoor air quality, to name a few: bad ventilation design and inadequate filtration system, contaminants from combustion sources, pollutants from toxic building materials and cleaning products, and outdoor pollutions that find their way inside the building. The health effects from regular exposure to poor indoor air quality can be long term with severe outcomes.

Reference standard

Indoor air quality alone is a category in the WELL building standard (45). It includes performance thresholds and encourages the monitoring of the following indoor air pollutants:

- Particulate matter (PM2.5, PM10)
- Carbon dioxide
- Nitrogen dioxide
- Organic gases (formaldehyde, VOCs)
- Inorganic gases (carbon monoxide, ozone)
- Total VOCs

Benchmarking

The purpose of this benchmarking is to encourage the monitoring of indoor air pollutants and provide a suggested benchmarking for the measurement levels. It is expected that most buildings do not measure all the parameters specified in WELL, but the following which is addressed in both fundamental and enhanced indoor air quality issues are proposed as a rating method based on WELL thresholds, as shown in Table 23.

Table 23. Benchmarking of KPI 12 – Indoor air quality

Formaldehyde (ppb)	Ozone (ppb)	CO (ppm)	PM2.5 (ug/m3)	PM10 (ug/m3)	CO_2 (ppm)	Score
> 40.4	> 76	> 30	> 25	> 50	> 1200	1
≤ 40.4	≤ 76	≤ 30	≤ 25	≤ 50	≤ 1200	2
≤ 27	≤ 51	≤ 9	≤ 15	≤ 40	≤ 900	3
≤ 20.2	≤ 38	≤ 7.5	≤ 12	≤ 30	≤ 750	4
≤ 13.4	≤ 25	≤ 6	≤ 10	≤ 20	≤ 600	5

Methodology

WELL also provides performance testing protocols to all the parameters within the Air category. Here are a few examples of the intervals that measurements should be recorded:

- PM2.5, PM10, CO_2, CO, ozone: at least once every minute for a minimum of one continuous hour.
- Formaldehyde: minimum of one continuous hour or according to reference standards
- Nitrogen dioxide: up to one hour
- Radon: minimum of 48 hours for passive testing samples, the entire length of performance verification for active testing samples

KPI 13 – DAYLIGHT EXPOSURE

Definition
This indicator aims to support the circadian and psychological health of the building occupants through adequate indoor daylight exposure.

Background
Studies show that sufficient access to daylight has positive health impacts on building users. Exposure to enough daylight reinforces the circadian rhythms, which drives the control system of body processes such as digestion, the release of hormones, body temperature, and sleeping cycles. As people nowadays tend to spend more time indoors than outside, this has led to a lack of daylight exposure, which causes depression symptoms and impairment of cognitive function affecting more than 300 million people worldwide. (46) Providing enough daylight to the building occupants increase their productivity, sleep quality and wellbeing.

Reference standard
Daylight exposure is measured using the spatial daylight autonomy (sDA), which is a metric that describes the annual sufficiency of daylight levels inside a building. It calculates the percentage of the indoor area that receives a minimum daylight illuminance level for a specific portion of the building's annual operating hours. Both LEED and WELL use an sDA of 300,50%, meaning that the analyze area must achieve on average at least 300 lux for 50% of the annual operating hours. The percentage of the area that is achieved for each floor can be demonstrated through computer simulations as shown in Table 24.

Table 24. LEED's Daylight credits

Average sDA 300,50%	Credits
≥ 40% of regularly occupied floor area	1
≥55% of regularly occupied floor area	2
≥75% of regularly occupied floor area	3

Benchmarking
Table 25 below shows the daylight exposure benchmarking for this indicator.

Table 25. Benchmarking of KPI 13 - Daylight exposure

Average sDA 300,50%	Score
<40 % of regularly occupied floor area	1
40-54 % of regularly occupied floor area	2
55-64 % of regularly occupied floor area	3
65-74 % of regularly occupied floor area	4
≥ 75 % of regularly occupied floor area	5

Methodology
Daylight simulation and the calculation of average sDA value should be performed following the IES LM 83 standard, Section 2.2.

In general, the following information is needed for the simulation:

- Exterior building geometry and obstructions
- Site plan & location
- Floor plan and furniture plan
- Interior finishes and surface reflectance
- Glazing specifications
- Glare-control device specifications
- Occupancy schedule
- Climate weather files and data

KPI 14 - THERMAL COMFORT

Definition
This indicator aims to ensure that the majority of building users find the thermal environment acceptable.

Background
Thermal comfort is often considered one of the most important factors for building occupants' overall satisfaction. It also presents the most basic goal of the building service systems: to properly heat or cool the indoor environment. Unfortunately, buildings these days still struggle to achieve this basic goal, as studies show that as many as 41% of office workers are dissatisfied with the thermal environment in their workplace. (47)

Reference standard
Two commonly used metrics for thermal comfort are predicted mean vote (PMV) and predicted percentage dissatisfied (PPD). PMV and PPD are very widely used indices to describe the levels of thermal comfort of the indoor environment. By definition, PMV is an index that predicts the mean value of votes by a group of people based on a 7-point comfort scale, while PPD predicts the percentage of thermal discomfort expressed by people feeling too cold or too warm inside the building. (48) These metrics are used in standards such as ASHRAE 55, ISO 7730, EN15251, and are used in WELL with the following requirements:

- 95% of regularly occupied spaces must achieve PMV levels within +/- 0.5 and PPD levels ≤ 10% for 98% of the standard occupied hours of the year
- All regularly occupied spaces must achieve PMV levels within +/- 0.7 and PPD levels ≤ 15%

Benchmarking
To simplify the benchmarking process, the levels for PMV would be within +/- 0.5 and PPD levels ≤ 10% for all occupied hours of the year, with the percentage of compliant spaces according to Table 26.

Table 26. Benchmarking of KPI 14 - Thermal comfort

Percentage of regularly occupied spaces achieve thermal conditions	Score
<80	1
80-84	2
85-89	3
90-94	4
95-100	5

Methodology
Calculations are found in the reference standards. Thermal comfort can be demonstrated by computer simulation of the building, using the design or actual data, local climate files and appropriate occupant factors such as clothing and activity levels.

KPI 15 – BACKGROUND NOISE

Definition
This indicator aims to ensure acoustical comfort by limiting the background noise level from the building HVAC system and other sources.

Background
Another factor affecting the building user satisfaction is noise level. As the open office concept is becoming an architectural trend in office buildings, noise from internal and external sources easily turns into a distraction to the occupants, reducing productivity and increasing the stress level. Acoustic performance is often compromised, but it has become a growing problem in offices worldwide. A study in the UK reports that 99% of the employees said their concentration was impaired by poor acoustics in the workplace. (49)

Reference standard
Building acoustics performance is a complex issue that is influenced by several factors. In WELL standard, the Sound category addresses the following acoustic strategies:

- Sound masking
- Background noise levels
- Speech privacy
- Sound isolation
- Sound absorption

These aspects are measured by specific performance metrics, for instance, sound pressure level (dBA), speech privacy potential (SPP), reverberation time (RT), internally generated noise (NC or NR), noise isolation class (NIC), sound insulation (Dw).

Benchmarking
The benchmarking for this indicator aims to establish criteria to promote design techniques that limit the background noise levels from HVAC appliances in office spaces, as presented in Table 27.

Table 27. Benchmarking of KPI 15 – Background noise

Background noise sound pressure level (dB)			**Score**
Single office	*Open office*	*Conference*	
>55	>60	>50	1
50-54	55-59	45-49	2
45-49	50-54	40-44	3
40-44	45-49	35-39	4
<40	<45	<35	5

Methodology
WELL provides testing methods for the mentioned performance metrics. However, since the purpose of this indicator is to promote good design techniques, a demonstration that the design is compliant with the acoustics criteria from the local building code would be sufficient to be benchmarked.

3.3.8 Wellbeing

This category focuses on improving the wellbeing of the building occupants. According to Naci and Ioannidis (50), wellbeing or wellness refers to an individual's physical, mental and social conditions that go beyond the common definition of health. Four indicators have been selected for this category: Water quality (KPI 16), Fruit and vegetable availability (KPI17), Physical and visual ergonomics (KPI 18) and Access to nature (KPI 19).

KPI 16 - WATER QUALITY

Definition
This indicator aims to promote the supply of good water quality to the building occupants.

Background
According to the World Health Organization (51), there are 785 million people in the world who lack basic drinking-water services. Nearly a third of the global population is drinking water from a contaminated source and by 2025 half of the people on the planet will live in the water-stressed area. Access to clean water and sanitation is a basic human right recognized by the UN General Assembly, and therefore buildings need to provide clean and safe drinking water to the users.

Reference standard
The fundamental water quality requirements defined in WELL is that the water delivered to the project for human consumption, handwashing and showers/baths meets the following threshold:

a. Sediment: turbidity less than or equal to 1.0 NTU.
b. Microorganisms: contains 0 CFU / 100 mL total coliforms (including E. coli)

Benchmarking
The benchmarking for water quality is according to turbidity level as shown to Table 28, providing that the same water also does not contain microorganisms.

Table 28. Benchmarking of KPI 16 - Water quality

Water turbidity level (NTU)	Score
>1.5	1
1.1 – 1.5	2
0.6 – 1.0	3
0.1 – 0.5	4
<0.1	5

Methodology
WELL provides test methods for water quality but for the assessment, a test report from reliable sources such as the municipal water quality report would be sufficient.

KPI 17 – FRUIT AND VEGETABLE AVAILABILITY

Definition
This indicator aims to promote the consumption of fruits and vegetables.

Background
Our health and the food that we eat are closely related. Good nutrition along with regular exercise is the best way to prevent chronic diseases. Yet, most people around the world do not consume the daily recommended fruit and vegetable servings of 400g. (52) Diet patterns around the world are increasingly relying on highly refined and packaged foods that high in sodium, sugar and refined fats. Food choices are influenced by personal, cultural and environmental factors. By increasing accessibility and availability of healthy food choices such as fruits and vegetables, buildings can play a role in supporting healthy eating behaviors and improving people's quality of life.

Reference standard
The provision of fruits and vegetables is a fundamental credit in WELL's Nourishment category. If foods are sold or provided daily within the building boundary, the requirement is that at least 50% of available options, including beverages, are fruits and/or vegetables.

Benchmarking
This indicator is benchmarked based on the ratio of available fruits and vegetable options to all the food options provided in the buildings, as seen in Table 29.

Table 29. Benchmarking of KPI 17 – Fruit and vegetable availability

Percentage of food options are fruits and vegetables	Score
0-19	1
20-39	2
40-59	3
60-79	4
80-100	5

Methodology
Information about the food options could be obtained from the food service provider and from the menu. Equation 17 is used to calculate the availability of fruit and vegetable options:

$$\% \ of \ fruits \ and \ vegetables = \frac{number \ of \ fruit \ \& \ vegetable \ options}{number \ of \ all \ food \ options \ provided} \times 100\% \tag{17}$$

KPI 18 – PHYSICAL AND VISUAL ERGONOMICS

Definition
This indicator aims to promote physical and visual ergonomics.

Background
Despite the widely common knowledge of the benefits of regular physical activity, nearly a quarter of the global adult population are not physically active, according to 2016 data. Even more concerning fact is that more than 80% of the world's population aged 10-19, who are the future generations of humankind, are not sufficiently physically active. The lack of physical activity is linked with conditions such as diabetes, cardiovascular disease, depression, stroke, dementia, and a rise in premature mortality. Our society needs to take action to provide individuals with more opportunities to be active, and one way to ensure that is through policies that encourage physical activity at jobs and workplaces. (53)

Reference standard
WELL's Movement concept includes strategies to promote active lifestyles through building design of spaces. One of the prerequisites is to provide basic ergonomic workstation furnishings to prevent musculoskeletal disorders (MSDs). To support physical ergonomics, employees need to have the possibility to alternate between sitting and standing through the provision of height-adjustable desks for at least 25% of the workstations. This can be fulfilled upon employee request and should be delivered within eight weeks since the requests are made.

Benchmarking
For office buildings where the employees spend many hours at their workstations, everyone must have the ability to stand up while working to reduce physical strain and improve ergonomic comfort.

Table 30. Benchmarking of KPI 18 – Physical and visual ergonomics

Percentage of all workstation desks that are height-adjustable	Score
0-19	1
20-39	2
40-59	3
60-79	4
80-100	5

Methodology
Equation 18 below is used to calculate the percentage of height-adjustable workstation desks in the building:

$$\%\ of\ height - adjustable\ desks = \frac{Number\ of\ desks\ that\ are\ heigh - adjustable}{Number\ of\ all\ workstation\ desks} \times 100\% \qquad (18)$$

KPI 19 – ACCESS TO NATURE

Definition
This indicator aims to support the occupant's mental wellbeing by incorporating the natural environment through the interior and exterior design.

Background
Mental health is a fundamental aspect of wellbeing throughout an individual's stages of life. It is a health condition in which people can live their life to the fullest, to cope with normal stresses of life and to contribute positively to society. Poor mental health leads to depression, anxiety disorders, abuse use of substances such as drugs and alcohol. Worldwide, millions of deaths per year are related to abuse use of alcohol while depression costs the economy an estimated USD 1 trillion due to loss of productivity. Up to half of the people with mental health conditions living in developed countries do not receive necessary treatment, while that number is significantly higher at 85% in developing countries. Through the incorporation of nature into the building design, stress and mental fatigue at the workplace can be mitigated and occupant mental wellbeing can be improved. (54,55)

Reference standard
Providing the occupants with access to the natural environment is one of WELL's key strategies to improve mental wellbeing within buildings. Nature-incorporated design can be a direct connection to natural elements such as plants, water, light and nature scenes; or indi-

rect connection to nature through natural materials, patterns, colors, images and space layouts. However, the 'access to nature' credit in WELL does not specify a certain quantitative method for the number of natural elements that should be incorporated. Instead, LEED's Open space is used as a reference for this indicator. A minimum of 30% of the total site area must be provided as outdoor space, of which at least 25% must be planted with two or more types of vegetation. LEED defines that an outdoor space must be physically accessible and be one of the following:

- a pedestrian or landscape area that encourages outdoor social activities
- a recreational or landscape area accessible for exercises and physical activities
- a landscape area with two or more types of plants providing all year visual interest
- a garden space as a community garden or urban food production
- preserved or created habitat

Green or vegetated roofs that are physically accessible can be used toward the vegetation requirement.

Benchmarking
To be benchmarked, a building must provide outdoor space that is equal to or greater than 30% of the total site area, including the building footprint. The levels of green space are shown in Table 31.

Table 31. Benchmarking of KPI 19 – Access to nature

Percentage of open space that is vegetated	Score
0-9	1
10-24	2
25-37	3
38-49	4
≥ 50	5

Methodology
For the calculation, the following parameters should be obtained:

- Total site area within the project boundary, including the building footprint
- Total area of open space, as defined by LEED
- Total area of open space that is vegetated

The following Equation 19 and Equation 20 are used to calculate the percentages of open space and green space compliance:

$$\%\ open\ space = \frac{Total\ area\ of\ open\ space}{Total\ building\ site\ area} \times 100\% \tag{19}$$

$$\%\ of\ green\ space = \frac{Total\ area\ of\ green\ space}{Total\ area\ of\ open\ space} \times 100\% \tag{20}$$

3.3.9 Demand-side flexibility

Demand-side flexibility is one of the two categories identified for the Energy Flexibility dimension. In a nutshell, the demand-side flexibility of a building describes its ability to adjust its energy outputs based on the signals of the grid or the power system. As buildings are responsible for a significant portion of global energy consumption, their flexible capability can help accelerate the transition toward a low carbon energy system. The flexibility factor (FF) is first introduced by Le Dréau and Heiselberg (56) in 2016 and has been recognized by the IEA EBC Annex 67 as a next-generation metric for energy flexible buildings.

KPI 20 - FLEXIBILITY FACTOR

Definition
This indicator demonstrates the building's ability to shift the energy use from high to low price periods

Background
Demand response and energy flexibility are often discussed as key strategies for the transition of the energy system towards clean and renewable energy future. The number of researches on the impact of building energy flexibility has increased in recent years, which led to the development of different demand-side flexibility-related indicators.

Reference standard
The flexibility factor developed by Le Dréau and Heiselberg measures the load shifting capability from high to low price periods. For a given cost reference, FF ranges from -1 to 1. If all energy is consumed during high pricing, FF maximizes at -1 and vice versa. According to Clauß et al. (57), the flexibility factor is adaptable to energy consumption, costs or GHG emissions.

Benchmarking
A high flexibility factor suggests that the building's energy consumption is shifted to low price periods. A flexibility factor of 1 means no energy consumption when the energy prices are high, hence a high score is given as seen in Table 32.

Table 32. Benchmarking of KPI 20 - Flexibility factor

Flexibility factor	Score
-1 to -0.7	1
-0.6 to -0.3	2
-0.2 to 0.2	3
0.3 to 0.6	4
0.7 to 1.0	5

Methodology
The flexibility factor for heating energy consumption is calculated using Equation 21:

$$FF = \frac{\int LPT\ l_{heating} dt - \int HPT\ l_{heating} dt}{\int LPT\ l_{heating} dt + \int HPT\ l_{heating} dt} \tag{21}$$

where:
FF is the flexibility factor
$l_{heating}$ is building's heating energy consumption
LPT is low price time
HPT is high price time

3.3.10 Load matching and grid interaction

Load matching and grid integration indicators are becoming more important, especially for net-zero energy buildings (NZEB). To achieve an annual zero energy balance, such buildings often need to produce electricity from on-site renewable sources. The grids are designed to handle the peak demands of buildings, but not the peaks from on-site generation. Therefore, the load matching and grid interaction are influential factors when designing a building's on-site renewable energy system. In their research paper contributing to the role of NZEBs on the future energy systems, Salom et al. (58) discovered that the cover factors, which include load cover factor (KPI 21) and supply cover factor (KPI 22), illustrate the inter-relationship between local demand and supply of energy, whereas the loss of load probability (LOLP) factor (KPI 23) indicates how often the building needs to rely on electricity supply from the grid.

KPI 21 – SELF-GENERATION

Definition
The proportion of electrical demand met by on-site generation

Background
Also known as the load cover factor, the self-generation factor is described as the percentage of the building's electrical demand covered by on-site electricity generation. (58)

Reference standard
The report of Subtask A by IEA Annex 52 (59) set out to find a set of indicators that can provide relevant information to the building owners and the local grid operators when information from building simulations are available at the design stage. It concludes that load and supply cover factors, together with the LOLP are sufficient indexes to describe the relationship between the building load and the on-site generation.

Benchmarking
Higher self-generation factor means the building can self-generate electricity for its own use without using electricity from the grid and is benchmarked as in Table 33.

Table 33. Benchmarking of KPI 21 – Self-generation

Self-generation (load cover) factor %	Score
0-19	1
20-39	2
40-59	3
60-79	4
80-100	5

Methodology
Self-generation factor is calculated using the following Equation 22:

$$\gamma_l = \frac{\int_0^T \min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_0^T l\,(t)dt} \qquad (22)$$

where:
γ_l is self-generation/load cover factor
t is time
g is the on-site generation
S is storage energy balance
l is load
ζ is energy losses

KPI 22 – SELF-CONSUMPTION

Definition
The proportion of on-site generation consumed by the building.

Background
Also known as the supply cover factor, the self-consumption factor represents a percentage of the on-site generation that is used by the building.

Reference standard
The report of Subtask A by IEA Annex 52 (59) set out to find a set of indicators that can provide relevant information to the building owners and the local grid operators when information from building simulations are available at the design stage. It concludes that load and supply cover factors, together with the LOLP are sufficient indexes to describe the relationship between the building load and the on-site generation.

Benchmarking
Similar to the self-generation factor, the self-consumption factor is also presented as a percentage, with high self-consumption means most of the on-site generation is consumed by the building and therefore a high score, as in Table 34.

Table 34. Benchmarking of KPI 22 – Self-consumption

Self-consumption (supply cover) factor %	Score
0-19	1
20-39	2
40-59	3
60-79	4
80-100	5

Methodology
Self-generation factor is calculated using the following Equation 23:

$$\gamma_s = \frac{\int_0^T \min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_0^T g(t)dt} \tag{23}$$

where:
γ_s is self-generation/load cover factor
t is time
g is the on-site generation
S is storage energy balance
l is load
ζ is energy losses

KPI 23 – GRID INDEPENDENCE

Definition
Percentage of time when on-site generation is less than the building's demand.

Background
The loss of load probability factor measures the annual proportion of hours that the building requires grid electricity to support normal building operations.

Reference standard
The report of Subtask A by IEA Annex 52 (59) set out to find a set of indicators that can provide relevant information to the building owners and the local grid operators when information from building simulations are available at the design stage. It concludes that load and supply cover factors, together with the LOLP are sufficient indexes to describe the relationship between the building load and the on-site generation.

Benchmarking
Opposite to the cover factors, the higher the LOLP factor means the building requires electricity import most of the time, demonstrating that the building is heavily dependent on the power grid. Benchmarking for this indicator is shown in Table 35.

Table 35. Benchmarking of KPI 23 – Grid independence

Loss of load probability %	Score
80-100	1
60-79	2
40-59	3
20-39	4
0-19	5

Methodology

Loss of load probability is calculated using the following Equation 24:

$$LOLP = \frac{\int_0^T f(t)dt}{T} \begin{Bmatrix} f(t) = 1, if\ ne(t) < 0 \\ f(t) = 0, if\ ne\ (t) \geq 0 \end{Bmatrix} \tag{24}$$

where:
LOLP is loss of load probability
t is time
T is the evaluation period
ne is net exported energy

3.4 Final index and level of award

All 23 indicators discussed in previous sections are used to form an overall score, presented as the BASS index. The index score is the average of all the indicator scores. The index describes the smartness and sustainability level of the building, as shown in Table 36.

Table 36. BASS smart and sustainable levels

Smart & Sustainable Class	Score
A+	4.5-5.0
A	3.5-4.4
B	2.5-3.4
C	1.5-2.4
D	0.0-1.4

The levels can be interpreted as followings:

- Class A+ is for buildings with outstanding performance, perhaps they can be considered as the smartest and most sustainable buildings there are.
- Class A is for buildings with very good performance, exceeding the minimum standards.
- Class B is for buildings with good performance, meeting the minimum standards.
- Class C is for buildings with low performance, but are approaching the minimum standards.
- Class D is for buildings with very low performance.

Similar to the same approach of energy labeling, the BASS system rates a building in a specific smartness and sustainability class using indicators derived from existing frameworks. This allows comparison of building performances and ranking of the building stock, taking into account different aspects of green construction, occupant health & wellbeing, and energy flexibility.

4 Case study: assessment of a new office building

4.1 Assessment methodology

The objective of the case study is to conduct an actual assessment of the BASS system on a new office building to investigate the performance of the building as well as the system itself in a real-world context. Since the indicators are derived from existing standards and framework and cover many different aspects, it is foresighted that the assessment would require an extensive collection of data, which takes a longer time than the limited time of the thesis work. Therefore, the chosen case study building is a building that has already been built and occupied and has achieved a green building standard so that the information can be easily extracted and analyzed. For example, a building energy simulation model would require initial data collection, building the model and running the simulation, which is not in the scope of this thesis. A green building certified building would have this kind of information available as it is often a mandatory task of the green building rating system.

4.2 Case study: a new office building

4.2.1 Basic information

The case study building, seen in Figure 6, is a new office building located in Espoo, Finland. The building was completed in spring 2019 and is currently a workplace for more than 1000 experts. Spanning over 6 floors, the total floor area is approximately 20 000 square meters of open offices, enclosed offices, meeting rooms, entertainment spaces, and a cafeteria. Located in a lively urban area with good access to the transportation network, including trains, buses, highways and bicycle networks, the building is easily accessible for the people working in it and visitors. A large parking building is built next to the building with electric vehicle charging points and dedicated bicycle storage that is big enough for more than 160 bikes. The façade of the building is covered with a large area of glazing, as well as big skylights aiming to provide maximum access to daylight and view for the occupants.

Figure 6. Bird's-eye view of the case study building. (60)

The building project began in 2015 that started with the integrative design process with participation and cooperation between all building stakeholders: building owner, contractor, designers, architects and IT.

4.2.2 Sustainability

Since the beginning, the building design intended to create an energy-efficient and smart office building. The building was designed to meet the requirements of sustainable development. It boasts several sustainability features that are listed below:

- Energy efficiency is the main focus: energy efficiency is considered during the design of heating and cooling systems, envelope and structural components, glazing materials, ventilation, and lighting solutions.
- The construction of the building is coordinated by the Healthy Building (Tervey talo) framework, which takes into consideration the durability and cleanliness in the construction process, as its monitoring continues throughout the life-cycle of the building.
- The hybrid geothermal-district heating system is the highlight of energy efficiency measures. The ground-source heat pumps produce up to 90% of the total heating demand with the remaining is provided by the local district heating network. The system is described in more detail in section 4.2.3.
- Additionally, a photovoltaic (PV) system is installed on the roof of the building, consisting of 133 solar panels producing an estimated 10% of the electricity required to operate the heat pumps.
- The materials, lighting, and acoustics are designed to support the wellbeing of the employees. The entire building is equipped with an LED lighting system that automatically adjusts according to the user needs and daylight.
- Landscape and yard design emphasize biodiversity and bring natural habitat into the building, such as green roof and indoor planting. Multiple plant species are placed in the working spaces to provide a feel of nature and help to relieve stress.

The case study building was awarded the LEED v4 Gold level environmental certificate as well as the WWF Green office certificate. It also achieved energy certificate class A according to the new building energy code 2018 for nearly zero energy buildings.

4.2.3 Heating and cooling

Heating in the building is supplied by two sources: geothermal heat pumps and district heating. The heat pumps provide 90% of the total building's heating demands, while district heating provides the remaining 10%. The geothermal heat pump system consists of:

- Closed-loop vertical boreholes,
- Heat pumps,
- Delivery network.

The ground loop is buried in the ground near the building. Fluid circulates through the loop to absorb or release the heat in the ground. In Finland, the temperatures at 500m below the ground surface are usually between 8-14ºC. In the winter, heat pumps remove the heat from the fluid and use it for heating purposes. The process is reversed in the summer for cooling the building. Geothermal heat pump technology takes advantage of free heat/cooling source in the ground, where the temperature is generally stable year-round. Heat pumps use 25-50%

less electricity than conventional heating/cooling systems. The ‘hybrid’ geothermal/district heating system can be seen in Figure 7 below.

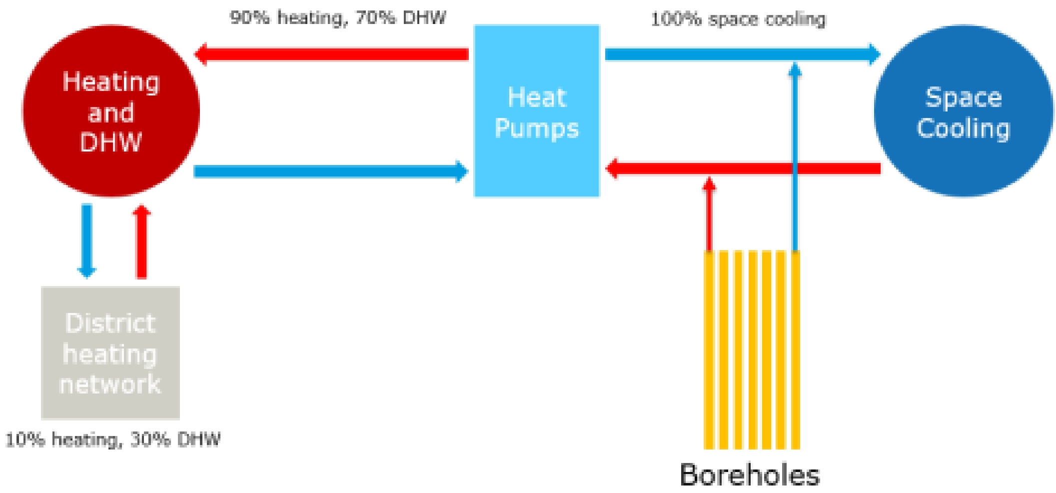

Figure 7. Illustration of the case study building’s heating and cooling system

The system has been optimized according to the hourly heating demands and energy prices. The building is also connected to the local district heating network to meet the high heating peaks when the geothermal system is unable to. Space cooling is provided in whole by the geothermal system. Air-handling unit cooling is provided by chillers.

4.2.4 On-site renewable energy

Besides geothermal, another source of renewable energy utilized is solar energy. The PV system (see Figure 8) consists of 133 solar panels installed on the roof of the building, with a total capacity of 35,2 kWp generating an estimated 34 400 kWh annually.

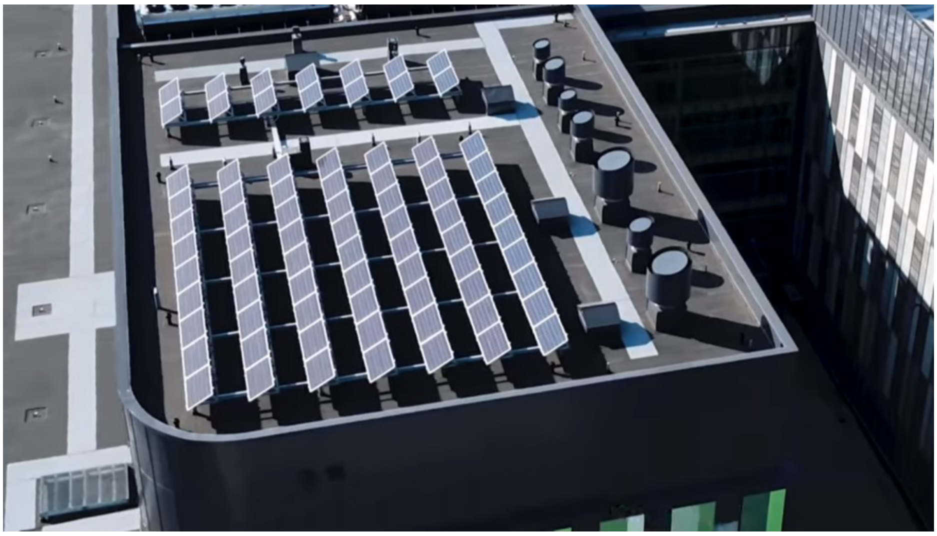

Figure 8. PV system in the case study building. (60)

5 Results and discussions

In this chapter, the results from the BASS assessment of the case study building are presented, followed by the discussion of the outcomes. In the discussion, the results are organized in different topics and explained in more detail.

5.1 Results

Using the BASS system developed in Chapter 3, an assessment has been carried out on a new office building in Espoo, Finland. For each indicator, initial information and data have been collected, analyzed and calculated to arrive at a performance score for the indicator. An average value of all the indicator scores is the final score of the BASS index. Using this method, the index aggregates the 'smartness' and 'sustainability' performance of a building into one number. The index is a quantitative presentation of different indicators which aims to provide a simplified, holistic and multidimensional view of a smart and sustainable building. The use of the BASS index gives a static overview of the performance of a building, but it can also be calculated regularly to track the performance of the building whether it is becoming more or less smart and sustainable, and to highlight the factors such as technologies or features that contribute to driving the performance. The results of the case study building are shown in Table 37 below.

Table 37. Results of the case study building's assessment

Indicator	List of indicators	Score
KPI 1	NOx emissions	4
KPI 2	Refrigerant impacts	4
KPI 3	Life cycle impact reduction	3
KPI 4	Construction and demolition waste	4
KPI 5	Land use	5
KPI 6	GHG emissions from energy use	4
KPI 7	Renewable energy	2
KPI 8	Water use intensity	4
KPI 9	Public transport accessibility	3
KPI 10	Bicycle storage availability	4
KPI 11	Space efficiency	5
KPI 12	Indoor air quality	3
KPI 13	Daylight exposure	1
KPI 14	Thermal comfort	3
KPI 15	Background noise	5
KPI 16	Water quality	5
KPI 17	Fruit and vegetable availability	3
KPI 18	Physical and visual ergonomics	5
KPI 19	Access to nature	2
KPI 20	Flexibility factor	2
KPI 21	Self-generation	1
KPI 22	Self-consumption	5
KPI 23	Grid independence	1
	Final score	**3.4**

The final result indicates that the case study building achieves a score of 3.4 out of a maximum 5, corresponding to BASS level B. This value suggests that the building, at its current state, is meeting the minimum levels of the assessed building standards and also excels in several areas. As seen in Figure 9, the score of 3.4 is at exactly the upper limit of class B, hence it would not take a lot of effort the case study building to move up to class A, which represents buildings with excellent performance and exceeding the minimum standards.

Case study building	**BASS Score**	**Smart & Sustainable Class**
	4.5-5.0	A+
	3.5-4.4	A
3.4	2.5-3.4	B
	1.5-2.4	C
	0.0-1.4	D

Figure 9. BASS classification of the case study building

The breakdown of the average score of each dimension is shown in Figure 10. The building achieves a score of 3.8 for green construction, 3.4 for health and wellbeing, and 2.3 for energy flexibility. The building is rated highly for its green features that contribute to the environment and the wellbeing and comfort of the occupants but leaves much to be desired in terms of energy flexibility.

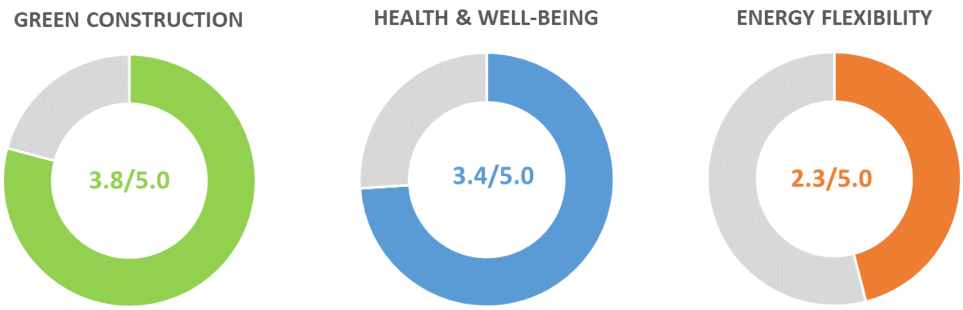

Figure 10. The average score of each dimension

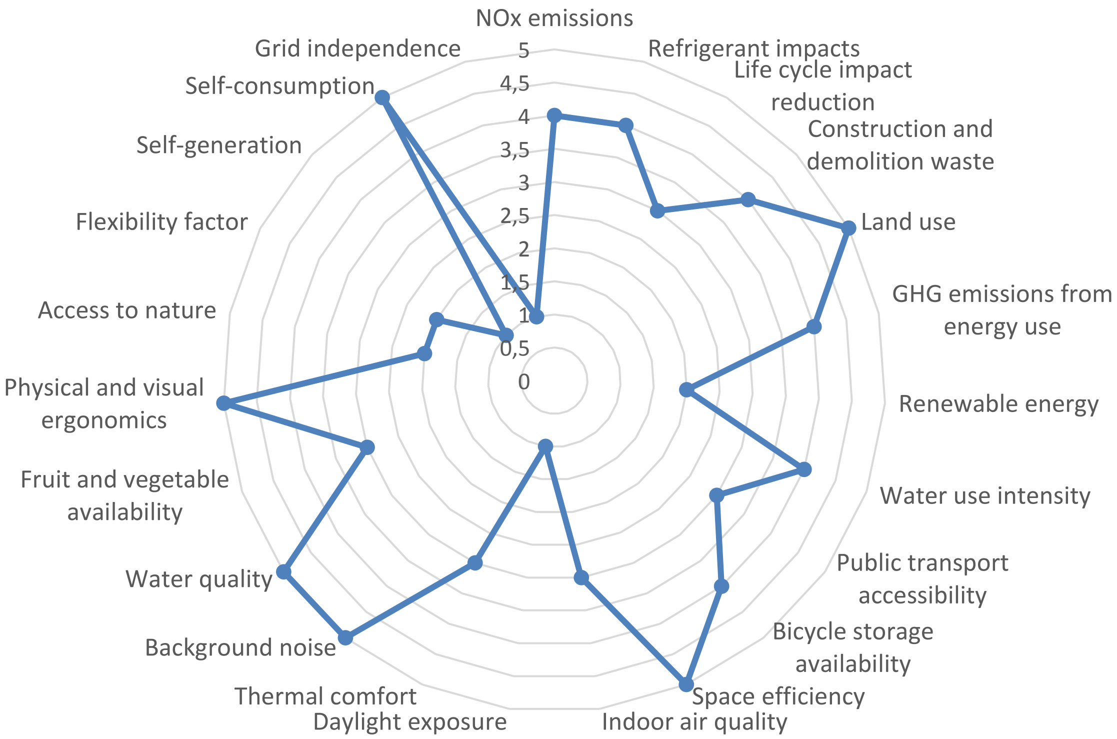

Figure 11. Radar chart of the case study building performance

From the radar chart found in Figure 11, it can be seen where the building performs well and where there is still room for improvement. As expected from the high green construction score, the building performs very well in most indicators in this dimension, even achieving the maximum score for sustainable land use and good space efficiency. Air pollution associated with the building operation is low thanks to low NOx emissions from the heating sources and minimal impacts from refrigerants used for heating and cooling systems. The building also meets the requirements of the green building standards for the life-cycle impact of the building's structure and envelope, greenhouse gas emissions from energy use, water use intensity and good accessibility of public transport. Despite using renewable energy for nearly 45% of the building's total energy demand, the building can only achieve a low score due to ground-source heat pumps not recognized as a renewable energy system in LEED.
There is a mix of high and low scores in the Health & Wellbeing dimension but generally, the performance is also good. Background noise (acoustic comfort), water quality, and ergonomics are the best features of the building in this dimension, followed by a sufficient level of thermal comfort and good availability of fruits and vegetables provided at the building's cafeteria. Access to nature and daylight is poor, so these are the areas where building owner could look into to improve the user experience. In the Energy Flexibility dimension, several low scores were given due to the lack of demand response strategy and relatively small on-site renewable production compared to the demand of the building's electrical load.

The flexibility factor indicates that most of the building's heating consumption is during the high energy price period.

5.2 Discussion of the results

This section discusses how the building has achieved such results and what they represent.

KPI 1 – NOx emissions
The building is scored 4 out of 5 for KPI 1 - *NOx emissions* thanks to its choice of heating sources. The ground source heat pump system which provides most of the building heating demand is powered by grid electricity and is considered to have zero NOx emissions, according to BREEAM compliance notes. The reason given for this consideration is because using grid electricity for heating purposes avoids the need for the combustion process and improves the local air quality. The heat from the local district heating network is calculated using Equation 1 to come to NOx emission value of 247 mg/kWh. The average NOx emissions of the building are then calculated with Equation 2 and the result is 23.8 mg/kWh.

KPI 2 – Refrigerant Impacts
KPI 2 - *Refrigerant Impacts* receives 4, also a good score. Total Direct Effect Life Cycle CO2e emissions (DELC) value is estimated to be 134.47 kgCO2e/kW coolth capacity, taking into consideration the refrigerants used for the geothermal heat pumps, chillers, and kitchen refrigeration units.

KPI 3 – Life Cycle Impact Reduction
The life cycle assessment had already been conducted for the building as part of the LEED version 4 certificate. The building achieved the minimum requirement of the three-credit Whole Building Life-cycle Assessment option, in which a minimum 10% reduction over the baseline in at least three categories, one of which must be global warming potential. As shown in Table 38, the LCA results demonstrated a 10.3% reduction over the baseline in the global warming potential category and therefore KPI 3- *Life Cycle Impact Reduction* obtains a score of 3 in the BASS system.

Table 38. LCA results of the case study building. (60)

Impact category	Unit	Baseline building results	Design case result	Reduction, %
Global warming potential (greenhouse gases)	$kgCO_2$ eq	1,56E+07	1,40E+07	- 10,3 %
Depletion of the stratospheric ozone layer	kgCFC-11 eq	1,72E+00	1,71E+00	-0,6 %
Acidification of land and water sources	$kgSO_2$ eq	4,25E+04	3,98E04	- 6,4 %
Eutrophication	PO_4^{3}eq	9,84E+03	5,35E+03	- 45,6 %
Formation of tropospheric ozone(photochemical oxidant formation)	C_2H_4eq	7,20E+03	5,95E+03	- 17,4 %
Depletion of non-renewable energy resources	MJ	1,44E+08	1,34E+08	-6,9%

Besides, the building also achieved 45.6% and 17.4% in eutrophication and formation of tropospheric ozone categories respectively, hence the LCA results would also qualify for 3 credits for the newer LEED version 4.1.

KPI 4 – Construction and Demolition Waste
According to the construction waste report, 85% of the total construction waste by weight is diverted away from landfills, with 32% is recycled and 53% for energy recovery. The diversion strategies help the building achieve a score of 4.

KPI 5 – Land Use
The building achieves a full score for KPI 5 - *Land Use* as it was constructed on previously developed land. According to the site assessment report done before the construction, the site area was a field consisting of landfilling and soil repositories. It was also used as a snow dump. The old aerial photographs and basic maps show that the area was a field in 1932. Between 1964 and 1991, there used to be 3 buildings likely used for residential purposes. The aerial view from 2005 shows a forested area about half of the site area. The buildings were demolished in 2005. According to the aerial photographs between 2009 and 2011, the southern and southwestern edges of the area were used to store site machinery, containers, and equipment. Aerial photographs between 2013 and 2016 show no site material or machinery stored in the area, but surplus land was imported.

KPI 6 - GHG Emissions from Energy Use
The building performs exceptionally in KPI 6 - *GHG emissions from energy use*, accomplishing a 78% of GHG emission reduction over the baseline building using energy simulation method (see Figure 12). This is a showcase of the energy efficiency features of the building: excellent building envelope, high performing building services systems and energy-efficient lighting. The most noticeable energy savings come from heating and cooling energy, as the hybrid system combining geothermal energy and district heating energy provides most of the building's heating and cooling demands while using relatively little electricity to operate the heat pumps. As the building utilizing heat from the ground in the winter and free cooling in the summer (by dumping the heat back to the ground), it significantly reduces the GHG emissions over traditional methods, hence receiving a high score of 4.

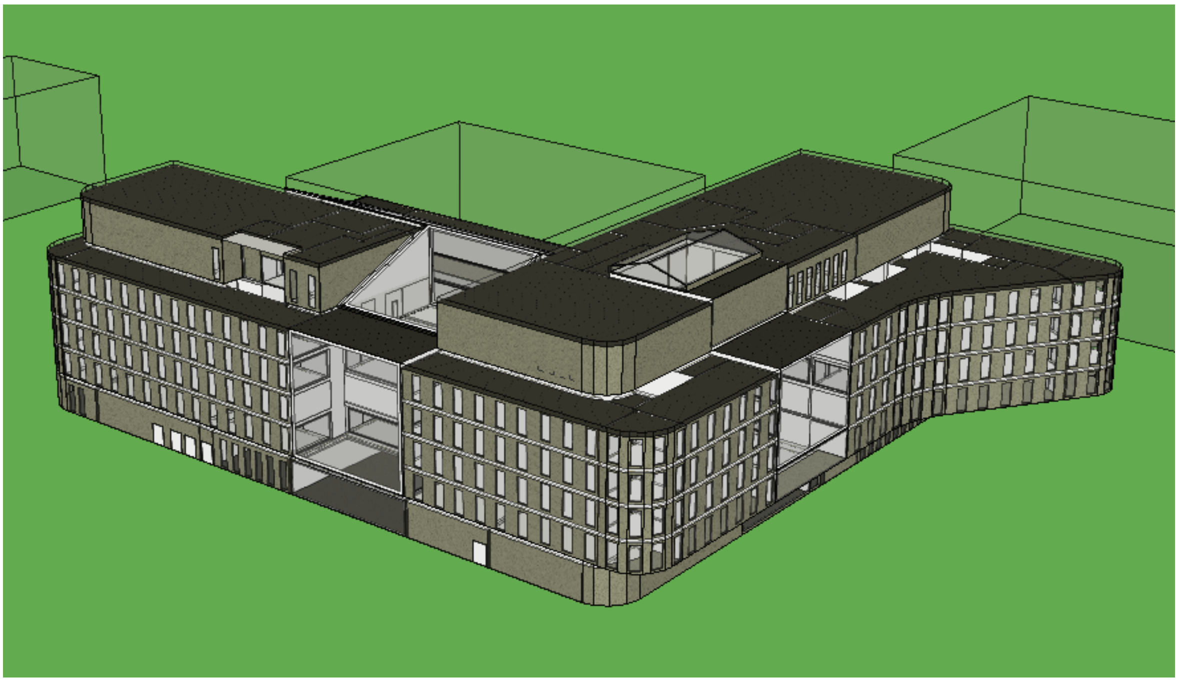

Figure 12. Energy simulation model of the case study building

KPI 7 – Renewable Energy

Despite the utilization of a renewable source (geothermal), the building is scored fairly low in KPI 7 - *Renewable Energy*, with a score of 2 because LEED does not recognize the ground-source heat pump as a renewable energy system. Eligible geothermal energy sources as renewable are, for example, electricity and steam generated from subterranean steam or hot water and not geothermal energy used together with vapor compression cycles as in this case. The only eligible renewable source in the building is the photovoltaic system, which produces approximately 3% of the annual total energy consumption, including heating, cooling, and electricity.

KPI 8 – Water Use Intensity

The calculations for LEED' Indoor Water Reduction credit are used to determine the score for KPI 8 - *Water Use Intensity*. According to the results, just a little over 41,1% water usage reduction over the baseline was achieved, earning a score of 4 for the building.

KPI 9 – Public Transport Accessibility

As seen in Figure 13, several bus stops are within 120-meter walking distances to the building's entrance, which connect the building to the city center and other parts of the city. The public transport's input data was entered into BREEAM's Tra01 calculator and an accessibility index of 4.84 was determined. This index corresponds to a score of 3 for KPI 9 - *Public Transport Accessibility*. It is worth to mention that a rapid bus stop seen in Figure 13 was not eligible for BREEAM, as the walking distance from the stop to the building is more than 650m. The main train station nearby was also not able to be included in the calculation due to the distance 500m further than the BREEAM-defined distance of 1000m.

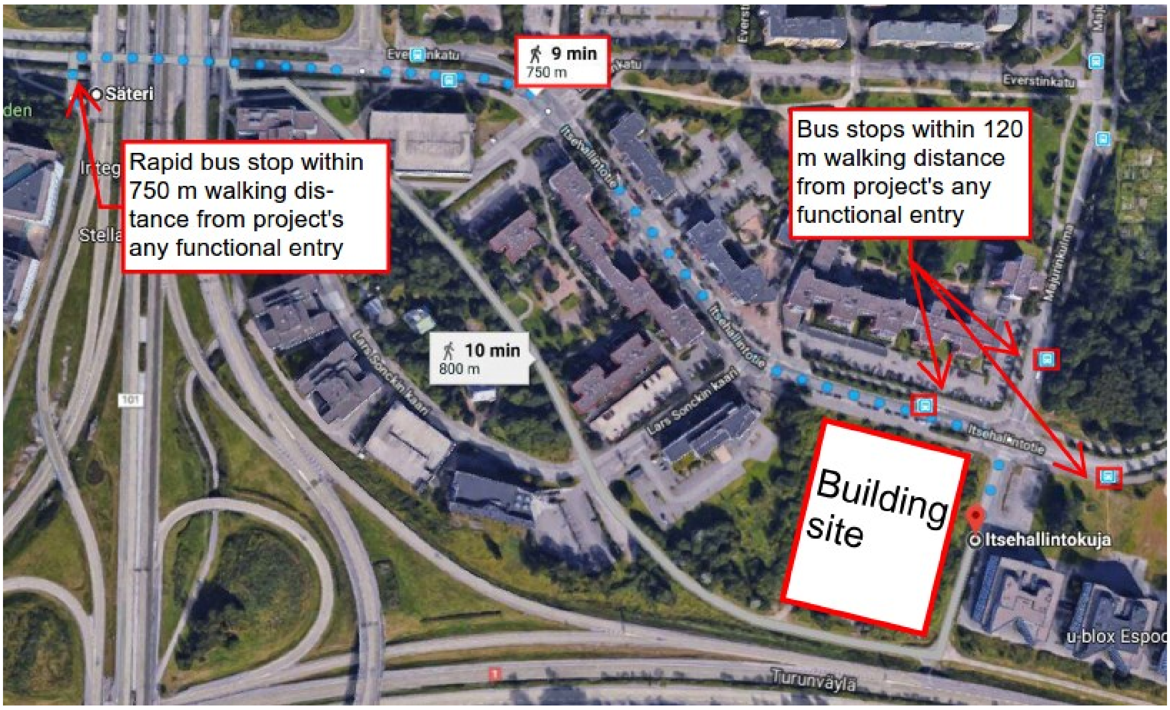

Figure 13. Public transport map for the case study

KPI 10 – Bicycle Storage Availability
The building was designed to encourage the use of bicycles among the staff. An amount of bicycle racks is provided in equivalent to 18% of the total building's regular occupants. This results in a score of 4 for the *Bicycle Storage Availability* indicator. The racks are installed in dedicated bicycle storage that is secured by an electronic door lock that only the employees can have access to, providing good security measures for the bike owners.

KPI 11 – Space Efficiency
For KPI 11 - *Space Efficiency*, the calculation is fairly straightforward. The usable area (UA) is estimated to be 16 227 m^2, while the gross floor area (GFA) is about 19 706 m^2. The space efficiency factor is thus 82%, which is a good ratio representing an efficiently designed office building. (61)

KPI 12 – Indoor Air Quality
As KPI 12 - *Indoor Air Quality* aims to encourage the monitoring of air quality pollutants of the indoor environment, the building is assessed for its monitoring of carbon dioxide. Designed according to the Finnish Indoor Air Class S2, the building's HVAC system needs to maintain the CO_2 concentration below the 900ppm level. For this reason, a score of 3 is given. A screenshot of the BMS system showing the real-time measurements from the CO_2 sensors can be seen in Figure 14, which shows a week's worth of measurement data in a meeting room of the building. The data shows that the sensors were able to detect different levels of carbon dioxide from the room users and that the levels are maintained below 900 ppm by the ventilation system.

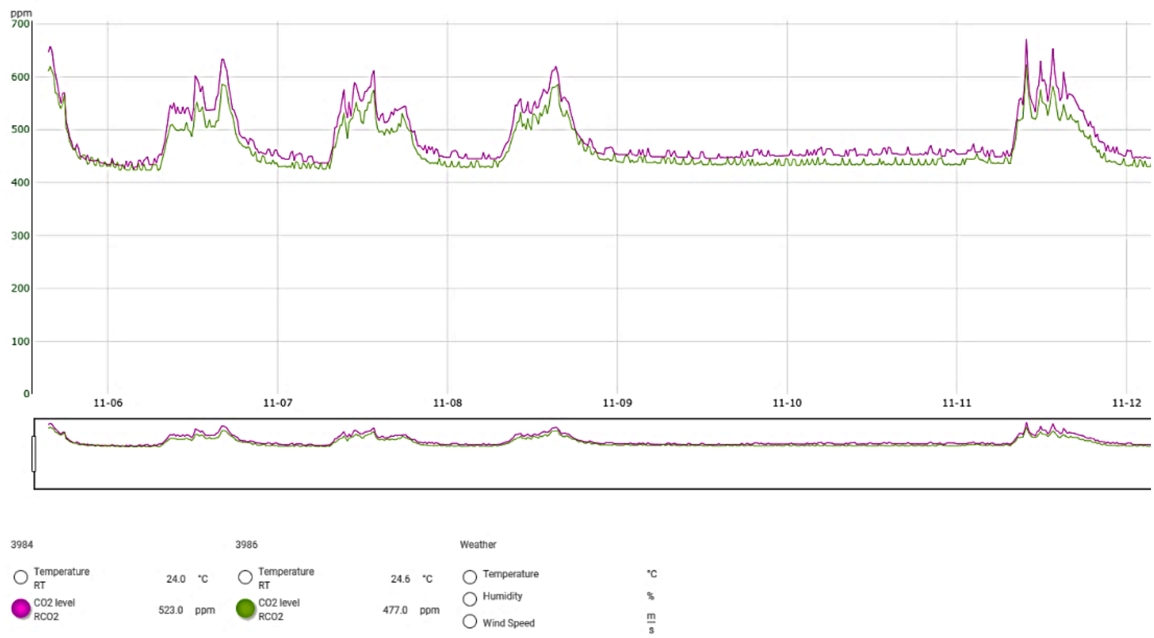

Figure 14 Example of CO_2 monitoring data in the case study building

KPI 13 – Daylight Exposure
Daylight simulations were carried out during the design phase to study the daylight exposure level of the interiors for a whole year. The study uses average $sDA_{300,50\%}$ as a metric, and the result is 37%, representing the percentage of the total regularly occupied floor area that

achieves at least 300 lux for 50% of the annual occupied hours. This has proven to be not enough to meet the minimum threshold of 40% in LEED version 4.1, and therefore a low score of 1 is given for KPI 9 - *Daylight Exposure* indicator. Annual daylight exposure is a challenging issue for building projects in Finland, as daylight amount varies greatly throughout the seasons. Because of the far north location, daylight is plenty during the summer months but is limited during the winter. (62) Figure 15 shows the daylight simulation result for one floor of the building. It can be seen from the figure that large areas of the floor (shown with red color) have inadequate access to daylight and need to rely on artificial lighting.

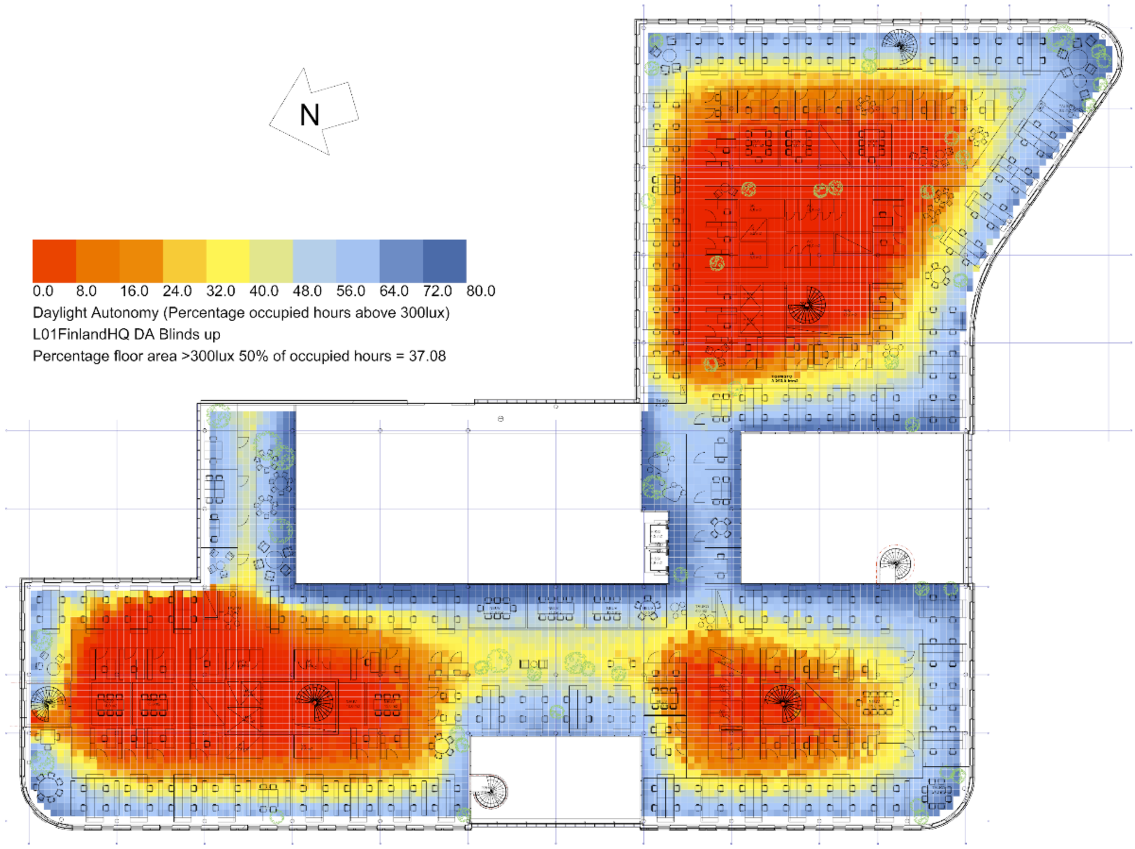

Figure 15. Daylight simulation result of the case study

KPI 14 – Thermal Comfort

The energy simulation model is used to study the indoor comfort level. Fanger's indices PMV and PPD are incorporated as outcomes of the simulation results, and the total area of regularly occupied spaces that achieves the limits is determined. With 88,6% of the occupied area where PMV and PPD fall within the range of thermal comfort, the building achieves a score of 3 for KPI 14 - *Thermal Comfort*. Figure 16 displays one floor of the thermal comfort simulation, where it shows that the PPD levels of most of the spaces are below the 10% level required.

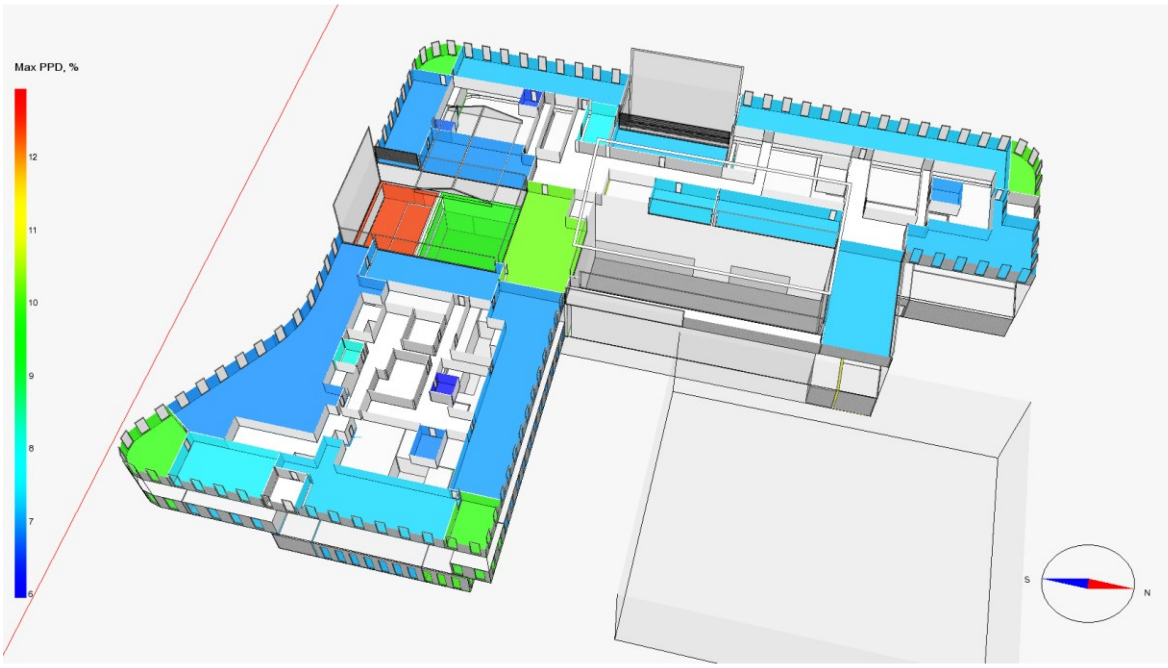

Figure 16. Thermal comfort simulation of the case study

KPI 15 – Background Noise

The acoustic environment of the building is designed according to class C of the standard SFS-5907 Acoustic classification of spaces in buildings. As shown in Table 39, the maximum permitted sound levels caused by HVAC equipment in the building are below the levels specified in the WELL standard, therefore a score of 5 is given for KPI 15 - *Background Noise*.

Table 39. Comparison of criteria in SFS 5907 and WELL

Room type	SFS 5907 (class C), dB	WELL standard, dB
Single office	35	40-50
Conference room	35	35-45
Open office	40-42	45-55

KPI 16 – Water Quality

Water is supplied to the building from the Helsinki Region Environmental Services Authority HSY's water network, which is known to have excellent water quality. In Finland, tap water is not only safe to drink but has also been found to be much cleaner bottled water, according to the National Institute for Health and Welfare (THL). It is, therefore, no surprise that the turbidity level of the HSY water, which is monitored daily, is significantly low. The level ranges from 0,05-0,06 NTU according to HSY water quality report, corresponding to a score of 5 – the highest score.

KPI 17 – Fruit and Vegetable Availability
The building has a restaurant that serves food, drink and catering services for the people working in it. To determine the amount of fruit and vegetable options provided, the menu of the restaurant has been examined. It is estimated that half of the food and drink options from the restaurant is fruits and vegetables, including salad option, vegetarian option, and fruits that are sold as desserts or snacks. This meets the *Fruit and vegetable availability* indicator criteria for a score of 3.

KPI 18 – Physical and Visual Ergonomics
The ergonomics of the workstations are paid with special attention to the building's facility management. Ergonomics education and instruction are provided to all the employees, encouraging everyone to adjust the workstations and changing the positions as often as possible to prevent muscular strains and injuries. All workstations in the building are equipped with height-adjustable desks, monitors and chairs. For this indicator, the building is awarded the highest score of 5.

KPI 19 – Access to Nature
Access to nature, on the other hand, only achieves a score of 2. This indicator looks at the open and green space availability of the building site. Figure 17 presents the building boundary within the red line, in which the red area indicates the building, blue area indicates the open space area of the building and the green area indicates the green space located next to the building. Despite the relatively large green space is located next to the building, it is not considered as part of the building development and therefore is not be counted toward this indicator. This is because LEED only recognizes open and green space that is within the project boundary. The site plan indicates that open space accounts for 56% of the total building footprint within the LEED boundary, of which only 12% is vegetated. A green roof on the top of the bicycle storage area also does not qualify as green space as it is inaccessible by the building users.

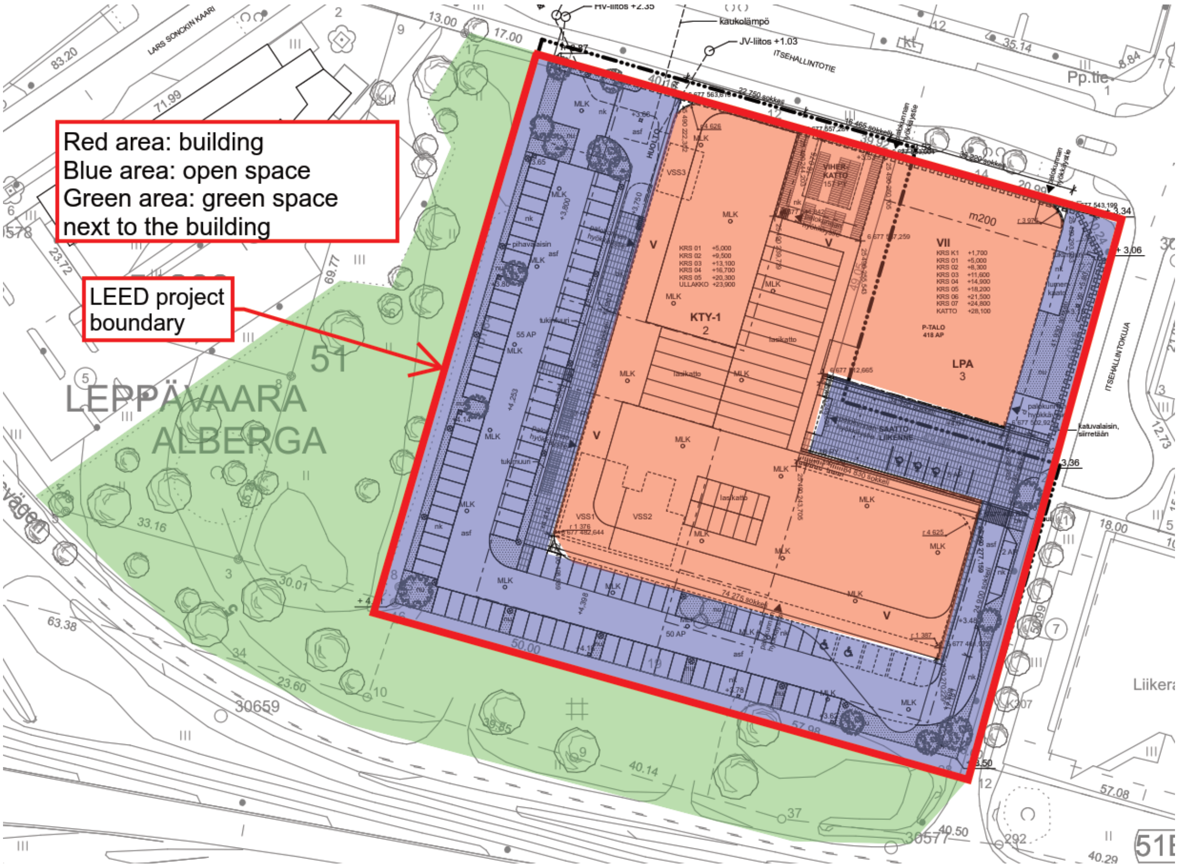

Figure 17. Open and green space availability of the case study building

KPI 20 – Flexibility Factor

The *Flexibility Factor* is calculated using hourly data of heating energy consumption and hourly electricity spot prices from the Nordpool market as cost reference for a calculation period of one month during the heating season. As most of the building's heating comes from the ground-source heat pumps operated by electricity, it is appropriate to use the electricity spot prices instead of the dynamic heating prices for the calculation. To indicate the high and low costs during the calculation period, the average cost of the period is determined. Hours with prices higher than the average are considered as high-price hours and hours with prices lower than the average are considered as low-price hours. The hourly price profile used as cost reference can be seen from Figure 18 below.

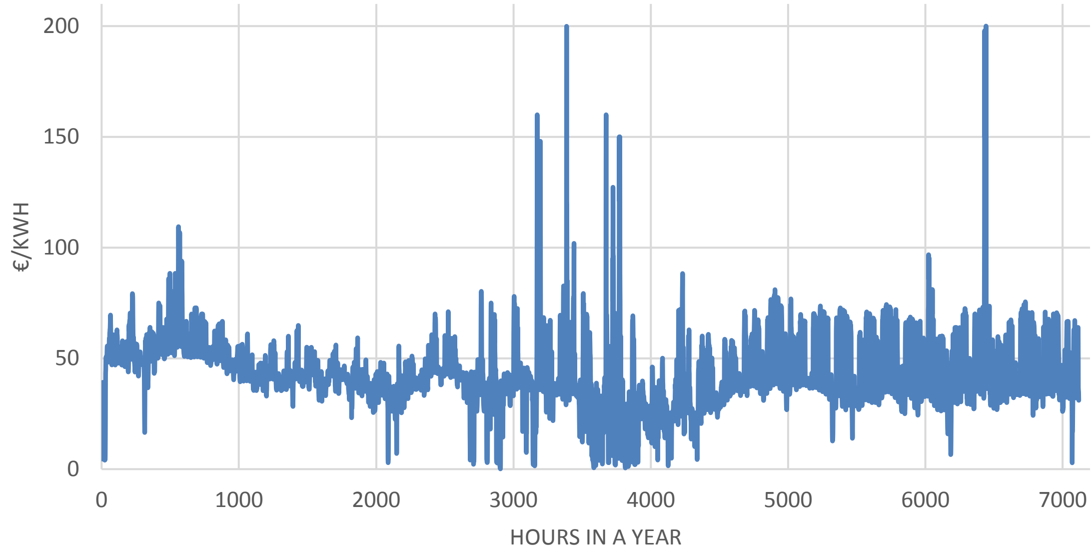

Figure 18. Nordpool market's hourly spot prices for the year 2019

Using Equation 21, the flexibility factor is calculated to be -0.41. This gives a quick indication that a large portion of heating energy in the building is consumed during the high price period, which is not desirable. Hence, a score of 2 is given based on the benchmarking levels.

KPI 21 & 22 – Self-generation and Self-consumption

Unfortunately, the actual solar energy production data is not available due to a lack of metering, so a simulation of the PV system is needed to calculate both KPI 21 - *Self-generation* and KPI 22 - *Self-consumption*. Hourly solar electricity production is simulated for one whole year and is used in the calculations following Equations 22 & 23. The results are 4% and 97.8% for self-generation factors and self-consumption factors respectively. It means that 4% of the building electricity demand is met by the PV system, while 97.8% of the PV production is consumed by the building. The self-generation factor is quite low but is expected considering the production of the solar panels and the electrical demand of the office building. On the other hand, the electricity produced on-site is effectively utilized most of the time.

KPI 23 - Grid Independence

Since the generation of on-site electricity is fairly low compared to the demand of the building, it is predicted that the building is heavily dependent on the grid. The LOLP factor is calculated to be 93.5%, showing the percentage of time during a year that the building needs grid import. This results in a low score of 1 for KPI 23 - *Grid Independence*.

5.3 Benefits and limitations of the framework

This section discusses the pros and cons of the assessment framework from the author's point of view. The following are the benefits of the BASS assessment tool can bring to the stakeholders:

1. For the building owners and developers, it provides a framework to support building planning and decision making. The system provides a list of KPIs selected from the most widely known certification systems which provide proven and reliable benchmarking and assessment methodologies. This allows informed decisions to be made on sustainable and technological capabilities to align with the objectives and budgets of the project buildings.
2. For the building management, it allows the measurement of progress towards smart and sustainable building goals, as the KPIs can be used to systematically collect data from the building operation. It is essentially a roadmap to reduce operational costs and increase profits.
3. For the policymakers, it helps set policy targets and monitor achievements by objectively assessing the value of green and intelligent buildings.
4. For solution providers, it gives better insight into business opportunities for smart solutions and green products so that they have a better understanding of their ability to meet the client's intelligence and sustainability goals.
5. For the occupants and the members of the public, it contributes to a better understanding of the building performance so that the industry is encouraged to provide better buildings for the society.

However, the methods of the BASS system are also subject to shortcomings and limitations:

1. The indicator selection is limited to the scope of the existing frameworks. These indicators often present the most proven and fundamental indicators, among all other issues that could also be desirable in enhancing the level of smartness and sustainability of a building. Several indicators are suggested for further research in the following section 5.4.
2. Some of the topics are challenging to quantify because they can be subjective. For example, wellbeing indicators focus on the building design features that contribute to better living conditions but are not able to measure the living quality from the user perspective, like what people feel and think, emotions and overall satisfaction, etc.
3. Also, some topics are multi-dimensional that are not fully reflected by a single indicator. Acoustic comfort, for example, has many influencing factors such as noise from the outside of the building, level of sound insulation of building materials and internally generated noise.
4. Only until recently that the interaction between buildings and the energy systems are gaining more attention. Energy flexible building is a developing research field that requires more time to mature. At the moment, the energy flexibility indicators selected for this framework are based on some of the most heavily researched indicators.

5.4 Further research

In this thesis, for benchmarking purposes, the system has been developed using indicators from the existing and developed frameworks to ensure the robustness of the assessment system. However, some of the indicators require a great amount of effort to be tracked and monitoring over time, while several indicators addressing urgent and pressing issues are not present. In this chapter, several indicators are listed (see Table 40) to be investigated as the next step of the development of the BASS tool, which will allow streamlined monitoring and tracking of the building performance during the operational phase.

Table 40. Suggested indicators for further research

Suggested indicators	Comments
Embodied carbon	Embodied carbon is the carbon emissions associated with the manufacture, transport, and construction of building materials, which are referred to as 'upfront carbon'. WGBC has called for coordinated actions to tackle the embodied carbon, with the target that all new buildings, infrastructure, and renovations must be net-zero embodied and operational carbon by 2050. This brings the light to embodied carbon which is an issue that often overlooked.
Building and material reuse	One of the most effective ways to reduce embodied carbon and preserve natural resources is to reuse and recycle buildings and building materials. There is a need to identify indicators related to the circular economy and to measure circularity performance.
Operational waste	Besides construction and demolition waste, waste from the building operation also has an impact on the environment and needs to be monitored.
Biodiversity index	DGNB's biodiversity index could give an insight into the general health of the ecosystem within a building boundary.
Transport	Several indicators that can be used to monitor the usage of alternative transport modes, such as rates of use of cycling facilities or the percentage of occupants that choose active and low carbon transportation choices.
Space occupancy and utilization	These metrics can help determine the amount of space is required and how efficiently the spaces are being used so that spaces are not wasted.
Life cycle cost	Life cycle costing is an important tool for integrating smart building technologies and systems. DNGB has developed an indicator for benchmarking life-cycle costs of buildings.
IAQ index	An index for indoor air quality should be developed that takes into account typical indoor air pollutants that might affect the wellbeing of the people.
Real-time indoor comfort	Besides air quality, thermal comfort and lighting quality are also important aspects that can be monitored and optimized in real-time.
Acoustic comfort	A single index that can combine acoustic performance metrics to demonstrate the on-going acoustic comfort level of the indoor environment.

Table 40. Suggested indicators for further research (continued)

Suggested indicators	Comments
Wellbeing tracking	Possibility to monitor the physical and mental wellbeing of the building occupants.
Energy flexibility	Other energy flexibility indicators should be studied and the results of the IEA EBC Annex 67 on energy flexibility factors would be interesting to look out for.

All in all, the vision is that the suggested indicators will enable an in-depth analysis of the building performance with the use of technological advancements such as artificial intelligence to effectively, systematically and continuously monitor and control the building systems that are actively adapting to the user needs while achieving optimal performance, creating a truly smart and sustainable building.

6 Conclusions

Building and construction sector is in the midst of a challenging yet exciting transition towards greener and smarter buildings. In the coming years, the way buildings are designed, built and operated will change as buildings must achieve a significant reduction of carbon emissions to ensure that severe consequences of global warming are preventable while meeting the increasing expectations of the building users and delivering value for the owners. Realizing these challenges, engineering and consulting firm Ramboll Finland Ltd. has decided to develop a new building concept called ‘Smart and Sustainable Buildings’. The objectives of this thesis were to identify a definition of this concept and to create an assessment framework to guide the development of smart buildings that also achieve the sustainability goals.

The main conclusions from the research were that both ‘green buildings’ and ‘smart building’ are very wide concepts that take into account different aspects of buildings, including green construction, occupant health and wellbeing, and energy flexibility. In order to understand the smart and sustainable building concept, it is necessary to have a holistic view of all these important aspects. Despite covering a wide range of topics, green buildings and smart buildings do share common features such as promoting energy efficiency, increasing the uptake of renewable energy and improving the user experience. The main findings of this research were reviewed below based on the research questions mentioned in Chapter 1, section 1.3.

1. What is the definition of a smart and sustainable building?

The first task of this thesis was to find a common definition of smart and sustainable buildings. From the literature research, it appeared that such definition was missing, which then steered the task to investigate the main features of green buildings and to examine the existing definitions of smart buildings. As a result, the key aspects of intelligence and sustainability perspectives in buildings were gathered and combined as followed:

A smart and sustainable building can be characterized by three main natures:

- For the environment: A building that, over its entire life cycle, has a net positive impact on the natural environment and the planet.
- For the people: A building that delivers the best user experience for the occupants - by intelligently leveraging data collection to effectively manage its systems to enhance comfort, productivity, health, and sustainability.
- For the energy system: A building that supports and accelerates the decarbonization of the energy systems through energy efficiency measures, clean renewable energy, and demand-side flexibility.

2. What are the key performance indicators of a smart and sustainable building?

From the identified definition of smart and sustainable buildings, the key performance indicators were derived from the existing frameworks. A shortlist of indicators was drawn up to form the basis of the BASS assessment framework. The indicators were listed in Chapter 3, section 3.1 or Appendix 1.

3. Can the performance of such buildings be measured?

An assessment using the BASS system was carried out on a case study building, which was a new office building in Espoo, Finland. The performance of the building was assessed using the information and data that is available, with calculation methodologies from the existing frameworks, resulting in a final score of the BASS index.

In conclusion, the BASS index aggregates the ‘smartness’ and ‘sustainability’ of a building into one number. The index is a quantitative presentation of different indicators which aims to provide a simplified, holistic and multi-dimensional view of a smart and sustainable building. Although the use of BASS index gives a static overview of the performance of a building, it can also be monitored regularly to track the performance of the building whether it is becoming more or less smart and sustainable, or to highlight the factors such as technologies or features that contribute to driving the buildings to perform better.

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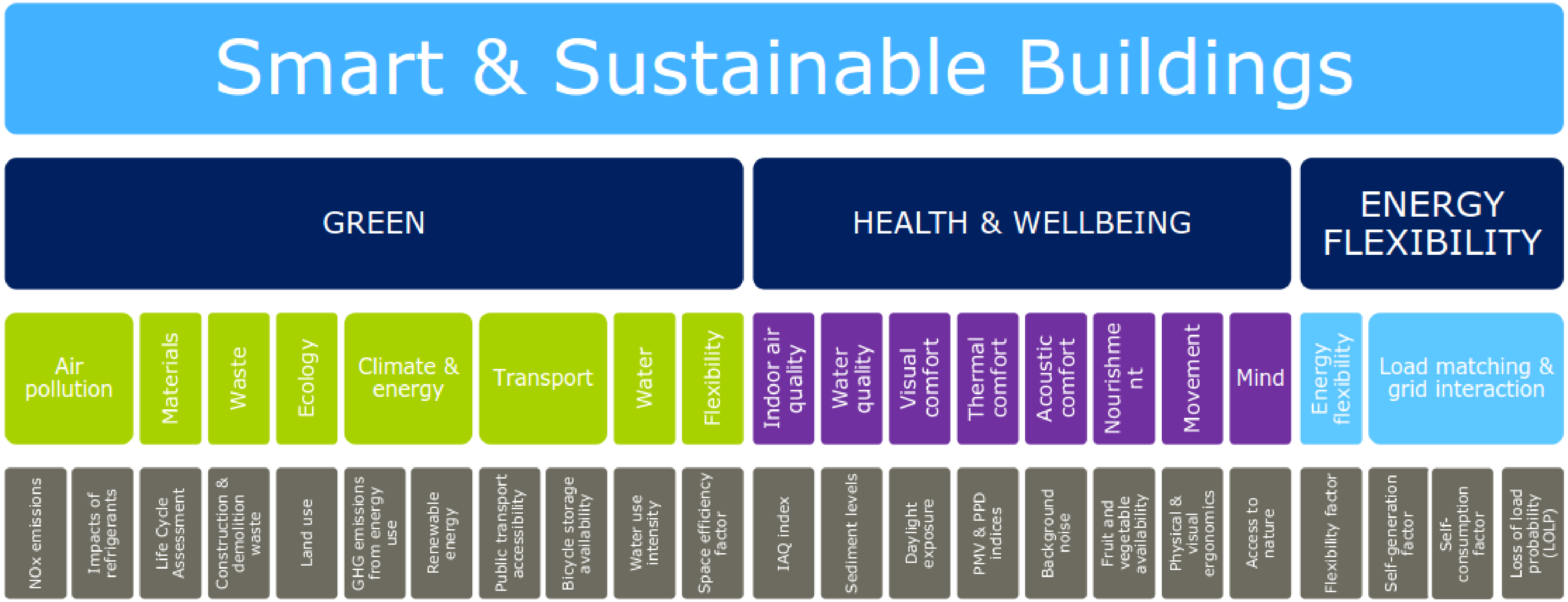
Appendices

Appendix 1 “Structure of BASS index”

BUILDING ASSESSMENT FOR SMARTNESS AND SUSTAINABILITY (BASS) INDEX



RAMBOLL

Dimension	Domain	Indicator identity	Indicator	Definition	Unit	Reference	Level 1	Level 2	Level 3	Level 4	Level 5	Data required
Green Construction	Air pollution	KPI1	NOx emissions	Amount of NOx emissions from space heating and hot water sources	mg/kWh	BREEAM	>72	57-72	41-56	21-40	0-20	Data required: For CHP systems: - Nox emissions (mg/kWh) per unit heat generated - Nox emissions (mg/kWh) per unit of fuel input - Heat output, kW - Electrical output, kW
		KPI2	Impacts of refrigerants	Amount of GHG emissions arising from the leakage of refrigerants used to heat or cool the building	kgCO2e/kW	BREEAM	>1000	700-1000	400-699	100-399	0-99	Data required: - R-number - System capacity, kW - Total refrigerant charge, kg - System operational life, yr - Refrigerant GWP - Annual leakage rate, % - Annual purge release factor, % - Annual service release, % - Probability of catastrophic failure, % - Refrigerant recovery efficiency, %
	Materials	KPI3	Life cycle impact reduction	Environmental impacts of products and materials throughout the building life cycle	% of GHG reduction	LEED	< 5	5-9	10-14	15-20	>20	Data required: - Bill of materials
	Waste	KPI4	Construction & demolition waste	Construction and demolition waste diverted away from landfills and incineration facilities	% of waste by weight	BREEAM	<50	50-59	60-84	85-94	95-100	Data required: - Construction and demolition waste data
	Ecology	KPI5	Land use	Use of previously occupied or contaminated land and avoid land which has not been previously disturbed.	% of the proposed development's footprint on previously developed land	BREEAM	<65	65-74	75-84	85-95	95-100	Data required: - Area of previously developed land - Area of the proposed development
	Climate, water and energy	KPI6	GHG emissions from energy use	Minimise operational energy and CO2 emissions	% improvement in energy performance – Greenhouse Gas Emissions	LEED	5-19	20-39	40-59	60-79	80-100	Data required: - Energy consumption per energy source - CO2 emission factor per energy source
		KPI7	Renewable energy	Reduce greenhouse gas emissions by increasing the supply of renewable energy	% of final energy consumption that is provided with renewable energy	LEED	<2	2-19	20-39	40-59	60-100	Data required: - Annual renewable energy production of the building - Annual building total energy use
		KPI8	Water use intensity	Reduce the consumption of potable water for sanitary use	% improvement over baseline building water consumption	LEED	<20	20-29	30-39	40-49	≥ 50	Data required: - List of water fixtures installed - Flow or flush rate of each fixture
	Transport	KPI9	Public transport accessibility	Encourage development in proximity of good public transport networks	Accessibility index	BREEAM	<2	2-3.9	4-5.9	6-7.8	≥ 8	Data required: - Map of building location and public transport nodes - Timetables for each service at each node
		KPI10	Bicycle storage availability	Promote the use of bicycle as a transport mode	% of bicycle storage needed	LEED	<5	5-9	10-14	15-20	≥ 20	Data required: - Number of regular building occupants - Number of bicycle storage racks provided
	Flexibility & adaptability	KPI11	Space efficiency	Ratio of usable and rentable space to the total building area	Space efficiency factor	DGNB	< 0.48	0.48-0.59	0.60-0.67	0.68-0.74	≥ 0.75	Data required: - Usable floor area (ISO 9836:1992) - Gross floor area ISO 9836:1992)
	Indoor air quality	KPI12	Indoor air quality	Carbon monoxide	ppm	WELL	> 30	≤ 30	≤ 9	≤ 7.5	≤ 6	Data required: - Measurement data from test reports or building management system
				Ozone	ppb	WELL	> 76	≤ 76	≤ 51	≤ 38	≤ 25	
				Formaldehyde	ppb	WELL	> 40.4	≤ 40.4	≤ 27	≤ 20.2	≤ 13.4	
				Carbon dioxide	ppm	WELL	> 1200	≤ 1200	≤ 900	≤ 750	≤ 600	
				PM2.5	mg/m3	WELL	> 25	≤ 25	≤ 15	≤ 12	≤ 10	
				PM10	mg/m3	WELL	> 50	≤ 50	≤ 40	≤ 30	≤ 20	
	Visual comfort	KPI13	Daylighting exposure	Connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space.	Average sDA300,50%	WELL	<40	40-54	55-64	65-74	≥75	Data required: - Building geometry and obstructions - Site plan and location - Floor plan and furniture plan - Interior finishes and surface reflectance - Glazing specifications - Glare-control device specifications - Occupancy schedules - Climate weather files and data
	Thermal comfort	KPI14	Thermal comfort	Ensure that the majority of building users find the thermal environment acceptable.	PMV and PPD	WELL	<80	80-84	85-89	90-94	95-100	Data required: - Building design data - Local climate files - Occupant factors (clothing, activity levels, etc.)

Health & Wellbeing	Acoustic comfort	KPI15	Background noise	Limiting the background noise level from the building HVAC system and other sources.	dB	WELL	Single office: >55 Open office: >60 Conference: >50	Single office: 50-54 Open office: 55-59 Conference: 45-49	Single office: 45-49 Open office: 50-54 Conference: 40-44	Single office: 40-44 Open office: 45-49 Conference: 35-39	Single office: <40 Open office: <45 Conference: <35	Data required: - Measurement data, test reports
	Water quality	KPI16	water quality	Limit the presence of sediment and water-borne bacteria levels in water for human contact.	turbidity (NTU)	WELL	>1.5	1.1-1.5	0.6-1.0	0.1-0.5	<0.1	Data required: - Test reports
	Noursihment	KPI17	Fruit and vegetable availability	Promote the consumption of fruits and vegetables by making fruits and vegetables easily accessible.	% of available options, including beverages, are fruits and/or vegetables.	WELL	0-19	20-39	40-59	60-79	80-100	Data required: - Information about food options from food service provider
	Movement	KPI18	Physical and visual ergonomics	Reduce physical strain and injury, improve ergonomic comfort and workplace safety and general wellbeing.	% workstations with height adjustable desks.	WELL	0-9	10-24	25-37	38-49	80-100	Data required: - Number of workstations - Number of workstations with heigh-adjustable desks
	Mind	KPI19	Access to nature	To create exterior open space that encourages interaction with the environment, social interaction, passive recreation, and physical activities.	% of the open space that is green space	WELL	<10	10-23	24-37	38-50	≥ 50	Data required: - Total building site area within project boundary - Total area of open space - Total area of green space
Energy Flexibility	Demand side flexibility	KPI20	Flexibility factor	Ability to shift the energy use from high to low price periods		Le Dreau & Heislberg, 2016	-1...-0.7	-0.6...-0.3	-0.2...0.2	0.3...0.6	0.7...1.0	Data required: - Hourly energy consumption data - Hourly cost data
	Load matching & grid interaction (LMGI)	KPI21	Self-generation factor	Proportion of electrical demand met by on-site generation	%	Salom et al, 2014	0-19	20-39	40-59	60-79	80-100	Data required: - Loads - On-site generation - Energy losses - Storage energy balance
		KPI22	Self-consumption factor	Proportion of on-site generation consumed by the building	%	Salom et al, 2014	0-19	20-39	40-59	60-79	80-100	Data required: - Loads - On-site generation - Energy losses - Storage energy balance
		KPI23	Grid independence	Time (%) when on-site generation is less than local demand	Loss of load probability %	Salom et al, 2014	80-100	60-79	40-59	20-39	0-19	Data required: - Building hourly electrical demand - On-site generation hourly data